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Station

Model Study of Marmet Lock Filling and Emptying System, Kanawha River, West Virginia

Hydraulic Model Investigation

by John E. Hite, Jr.

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Prepared for U.S. Army Engineer District, Huntington

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U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

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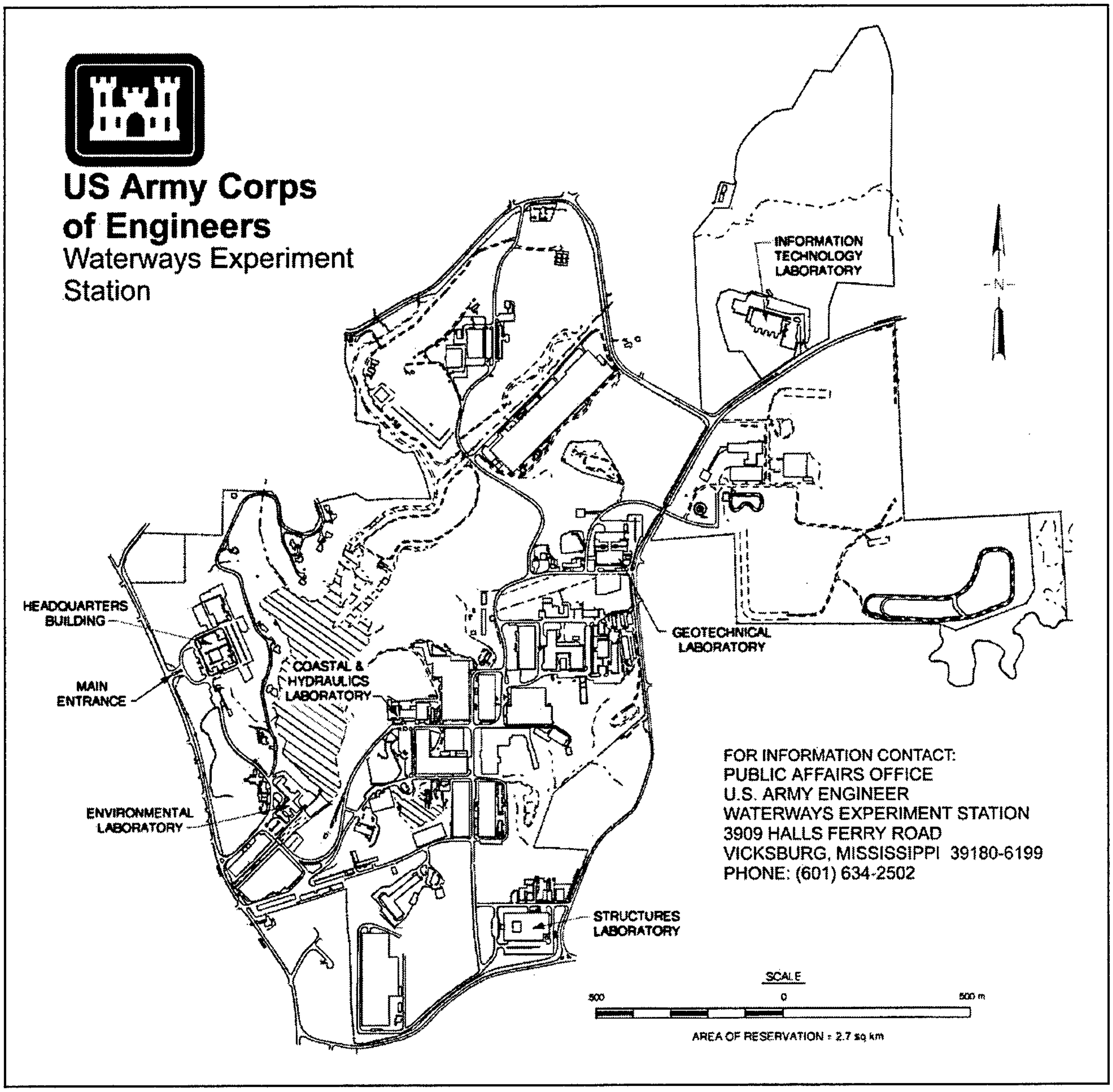

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Preface

The model investigation reported herein was performed for the U.S. Army Engineer District, Huntington. This study was authorized by the Huntington District on 1 October 1996, and Mr. Coy Miller, Huntington District, directed the study.

The work was conducted in the Coastal and Hydraulics Laboratory (CHL) of the U.S. Army Engineer Waterways Experiment Station (WES) during the period of October 1996 to March 1998 under the direction of Dr. James R. Houston, Director, CHL; Mr. Charles C. Calhoun, Jr. (retired), Assistant Director, CHL; and Dr. Phil G. Combs, Chief, Rivers and Structures Division, CHL. WES is a complex of five laboratories of the Engineer Research and Development Center (ERDC).

The experimental program was led by Mr. Joe E. Myrick under the supervision of Dr. John E. Hite, Jr., Leader, Locks and Conduits Group, CHL. Dr. Richard L. Stockstill, Spillways and Channels Branch, CHL, was consulted throughout the investigation for assistance in data analysis and results. Model construction was performed by Messrs. J. A. Lyons, M. A. Simmons, and C. H. Hopkins, Model Shop, Department of Public Works, WES, under the supervision of Mr. J. Schultz, Chief, Model Shop. Data acquisition and remote-control equipment were installed and maintained by Messrs. S. W. Guy, L. Koestler, and T. Nisley, Information Technology Laboratory (ITL), WES. Data acquisition software was developed by Dr. B. W. McCleave, ITL. The report was written by Dr. Hite and was peer reviewed by Dr. Stockstill.

During the course of the model study, Messrs. Jerry Webb, Coy Miller, David Margo, Demi Mack, Dave Moore, and Mike Worley, Huntington District; Ray Povirk, Pittsburgh District; Gordon Lance and Lyn Richardson, Great Lakes and Ohio River Division; Tom Way, DINAMO; Nelson Jones and Bill Barr, Madison Coal & Supply; Marlin Chaplin, Kanawha River Towing; David Reed, Crounse Corporation; Ray Thornton, Ohio River Co.; Dick Ehringer, Monogahela River Towing; Bob Taylor and John Reynolds, Sr., American Electric Power River; and David Smith, Ashland Petroleum (representatives of the navigation industry), visited WES to observe model operation, review experiment results, and participate in experiment planning.

At the time of publication of this report, Commander of ERDC was COL Robin R. Cababa, EN.

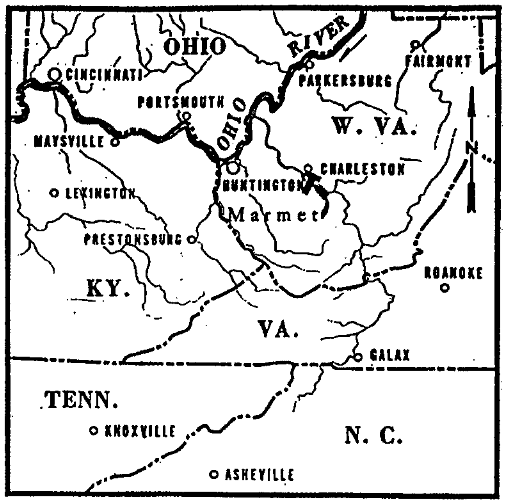
1 Introduction

Background

Many Corps Districts are facing the challenge of increasing the lockage capacity at their projects to accommodate increases in tow traffic. Four Corps Districts—Louisville, Huntington, Pittsburgh, and St. Louis—formed an Innovative Lock Design team, pooled their resources, and initiated a study with the U.S. Army Engineer Waterways Experiment Station (WES) to find innovative ways to reduce construction and operation and maintenance costs of navigation structures. This team agreed that large savings in construction costs could be realized if the lock intakes could be placed in the upper miter sill and the lock filling and emptying culverts could be placed inside the lock chamber rather than in the lock walls. This filling and emptying system with the culverts located inside the chamber was designated an In-Chamber Longitudinal Culvert Filling and Emptying System (ILCS). A ILCS design was developed for the lock addition at the McAlpine navigation project in the Louisville District, and the navigation improvements planned for the Marmet navigation project also provided a desirable site to investigate the use of an ILCS for filling and emptying the lock.

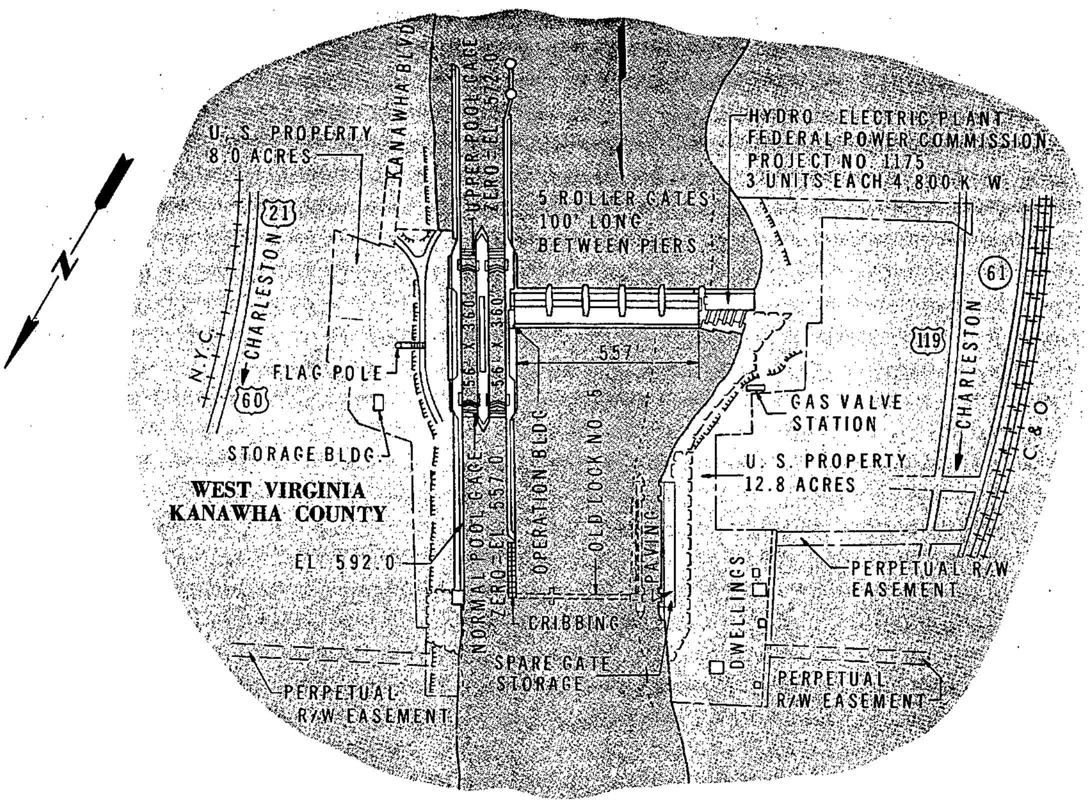
Prototype

The existing Marmet Locks and Dam project is located on the Kanawha River, 108.7 km (67.5 miles) above the mouth of the river (Figure 1). The upper pool extends upstream 24.2 km (15.01 miles) to the London Locks and Dam, and the lower pool is formed by the Winfield Locks and Dam about 58.4 km (36.3 river miles) downstream. The project consists of twin locks 17.069 m (56 ft) wide by 109.728 m (360 ft) long constructed of concrete gravity-type walls with horizontally framed miter gates. Concrete sills beneath the miter gates are anchored to the supporting rock foundation. Upper concrete guard and guide walls are supported by timber-bearing piles. The lower guard and guide walls are the concrete gravity type. Description of lock features and nomenclature used in this report can be found in Engineer Manual (EM) 1110-2-1611



VICINITY MAP

50 0 50 100 150



PLAN

500 0 250 500

SCALE IN FEET

Figure 1. Vicinity map and plan view of project

"Layout and Design of Shallow-Draft Waterways," EM 1110-2-2602 "Planning and Design of Navigation Locks," and EM 1110-2-1604 "Hydraulic Design of Navigation Locks." Filling and emptying is accomplished through side ports in the lock walls supplied by longitudinal culverts inside the lock walls. Flow to the culverts is controlled by stoney gate valves. The locks are emptied through wall openings into the lower lock approach channel near the lower miter gates.

The dam consists of five roller-type gates, each of which spans 30.480 m (100 ft) between concrete piers surmounted by reinforced-concrete tile-roofed machinery houses containing the gate-lift hoist equipment. A three-unit hydroelectric power plant of 144,000-kW capacity is located at the abutment end of the dam. This power plant is owned by the Kanawha Valley Power Company.

Improvements to the project to enhance navigation include construction of an additional lock. The new lock will be located on the east side of the existing locks and will be 265.176 m (870 ft) from pintle to pintle and 33.553 m (110.08 ft) wide. The design lift is 7.315 m (24.00 ft), which occurs with the normal upper pool elevation[1] of 179.832 (590 ft) and a normal lower pool elevation (el) of 172.517 (566 ft). The lock discussed in this report features a through-the-sill intake, a longitudinal in-chamber filling and emptying system, and a conventional sidewall discharge manifold similar to the design used on the Red River Lock 1. The outlet design also has features similar to the wall manifold design shown in Plate 4-2 of EM 1110-2-1604 and in Figure 70 of Davis (1989) except the Marmet design does not use baffles.

Many of the design features proposed for the Marmet Lock Addition project will result in considerable savings in construction costs if these features are shown to be hydraulically and structurally acceptable. Placing the lock intake in the upper miter gate sill saves an enormous amount of concrete that would be needed if the intakes were placed in the upper approach walls. Also, placing the filling and emptying culverts inside the lock chamber allows the flexibility of using different construction techniques for the lock walls. The more conventional construction of lock walls requires large concrete gravity walls with the culverts inside the walls.

The results of the Innovative Lock Design studies indicated it was feasible to construct the intakes through the upper sill and the culverts between the lock walls for a 387.096-m (1,270-ft) pintle-to-pintle length and a 33.552-m- (110.08-ft-) wide chamber. The model studies for the

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[1] All elevations (el) cited herein are in meters above National Geodetic Vertical Datum (NGVD) and (feet) above NGVD.

Innovative Lock Design Program evaluated the performance of the ILCS and the vortex tendencies in the upper intake approach during filling.[1,2]

Purpose and Scope

The purpose of the model study was to evaluate and make modifications to the filling and emptying system if necessary to provide a design acceptable to the Huntington District and the Towing Industry for the Marmet Lock Addition. As mentioned, a filling and emptying design with features similar to Marmet Lock was modeled for the McAlpine Lock Project. Since the length of the Marmet Lock was smaller than the McAlpine design, model experiments were necessary to check the adequacy of this design with a shorter length and to determine the operational characteristics.

Specifically, the study was to determine the following:

a. Performance of the through-the-sill intake.

b. Filling and emptying times for various valve speeds at the design lift of 7.315 m (24 ft).

c. Flow conditions and motion characteristics of unmoored barges in the lock chamber during filling and emptying operations.

d. Hawser forces exerted on barges moored in the lock chamber for various valve speeds at the design lift of 7.315 m (24 ft).

e. Pressures in the culverts.

f. Performance of the discharge outlet manifold.

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1 U.S. Army Engineer Waterways Experiment Station, Coastal and Hydraulics Laboratory, Rivers and Structures Division, 31 July 1996. Memorandum for Commander, U.S. Army Engineer District, Louisville, Subject: Data Report, Filling and Emptying Model Study for the Innovative Lock Design, McAlpine Lock.

2 U.S. Army Engineer Waterways Experiment Station, Coastal and Hydraulics Laboratory, Rivers and Structures Division, 30 September 1996. Memorandum for Commander, U.S. Army Engineer District, Huntington, Subject: Data Report, Model Study of Marmet Intake.

2 Physical Model

Description

The 1:25-scale model reproduced 182.880 m (600 ft) of the upstream approach including a portion of the right guide wall and the left guard wall. The intakes, miter gates, entire filling and emptying system including culverts and valves, discharge outlet manifold, and approximately 91.444 m (300 ft) of the topography downstream from the outlet were also reproduced. The intake, outlet, and filling and emptying system were constructed of a plastic material, and the lock walls, floor, and upper and lower approaches were constructed of plastic-coated plywood.

Details of the Type 1 (original) lock design are shown in Plates 1 and 2. The filling and emptying system begins with a multiported intake located in the upstream face of the miter gate sill. Each port is 3.000 m (9.84 ft) wide by 4.500 m (14.76 ft) high at the face of the intake. Figure 2 shows the model intake looking downstream. Each half of the intake transitions to 4.000-m- (13.12-ft-) wide by 4.500-m- (14.76-ft-) high culverts located outside the lock walls where the filling valves and bulkheads are located. The filling valve well is shown in Figure 3. Downstream from the filling valve, the culverts curve back into the lock chamber and continue to the filling and emptying manifold, which begins at Sta 0+68.776 B (stations in meters increasing in the downstream direction). The filling and emptying manifold consists of the two 4.000-m- (13.12-ft-) wide by 4.500-m- (14.76-ft-) high culverts with 11 pairs of ports located in both the upstream and downstream portions of the lock chamber as shown in Plates 1 and 2. The upstream ports contain additional port extensions to direct the filling jets normal to the culverts. The in-chamber longitudinal culvert filling and emptying system is shown in Figure 4. Downstream from the filling and emptying manifold, the culverts turn back outside the lock walls to accommodate the emptying valves and bulkheads (Figure 5). The discharge outlet is a multiported type with the face of the outlet located along the lock wall in the lower approach as shown in Figures 5 and 6.

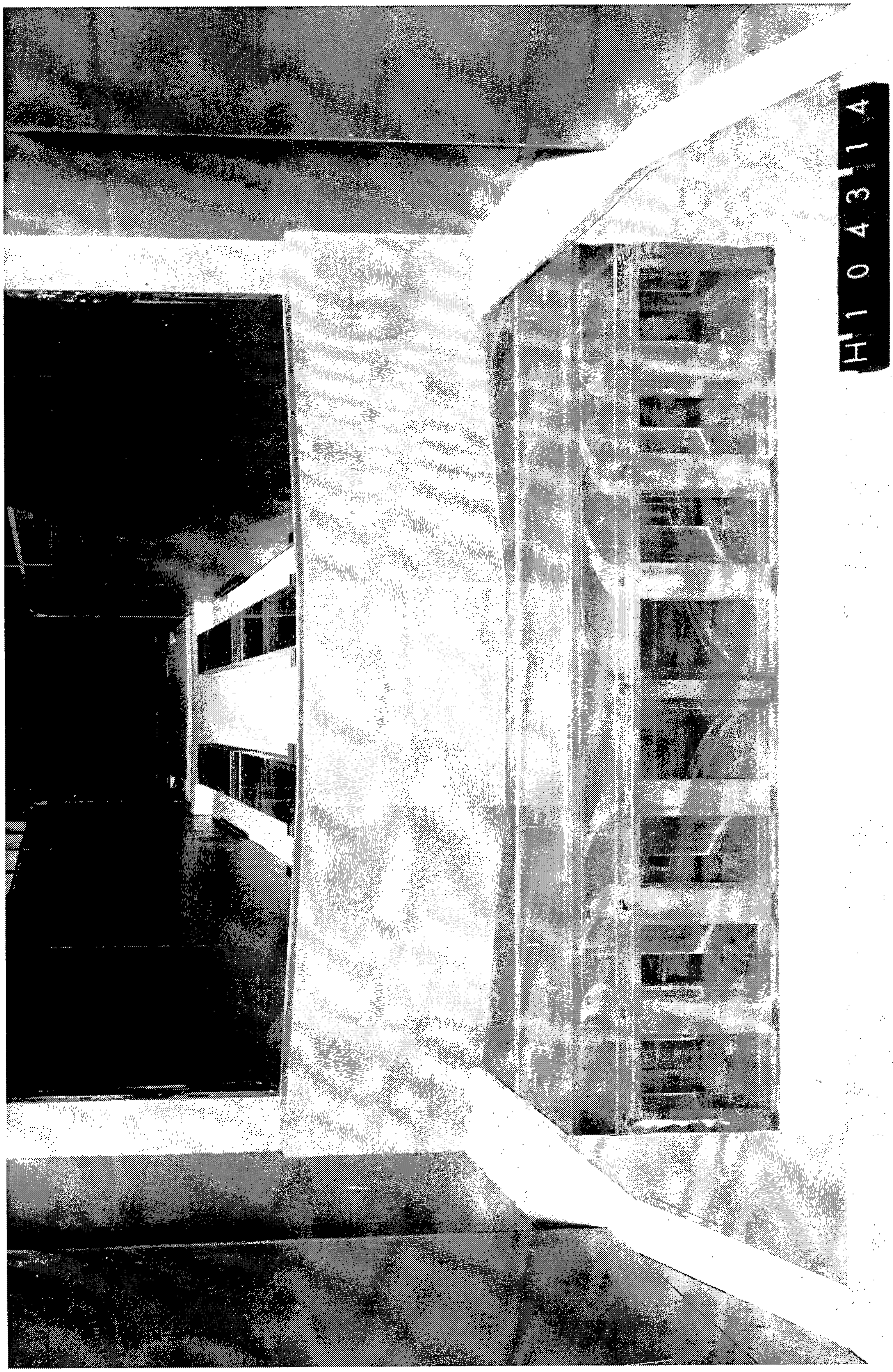
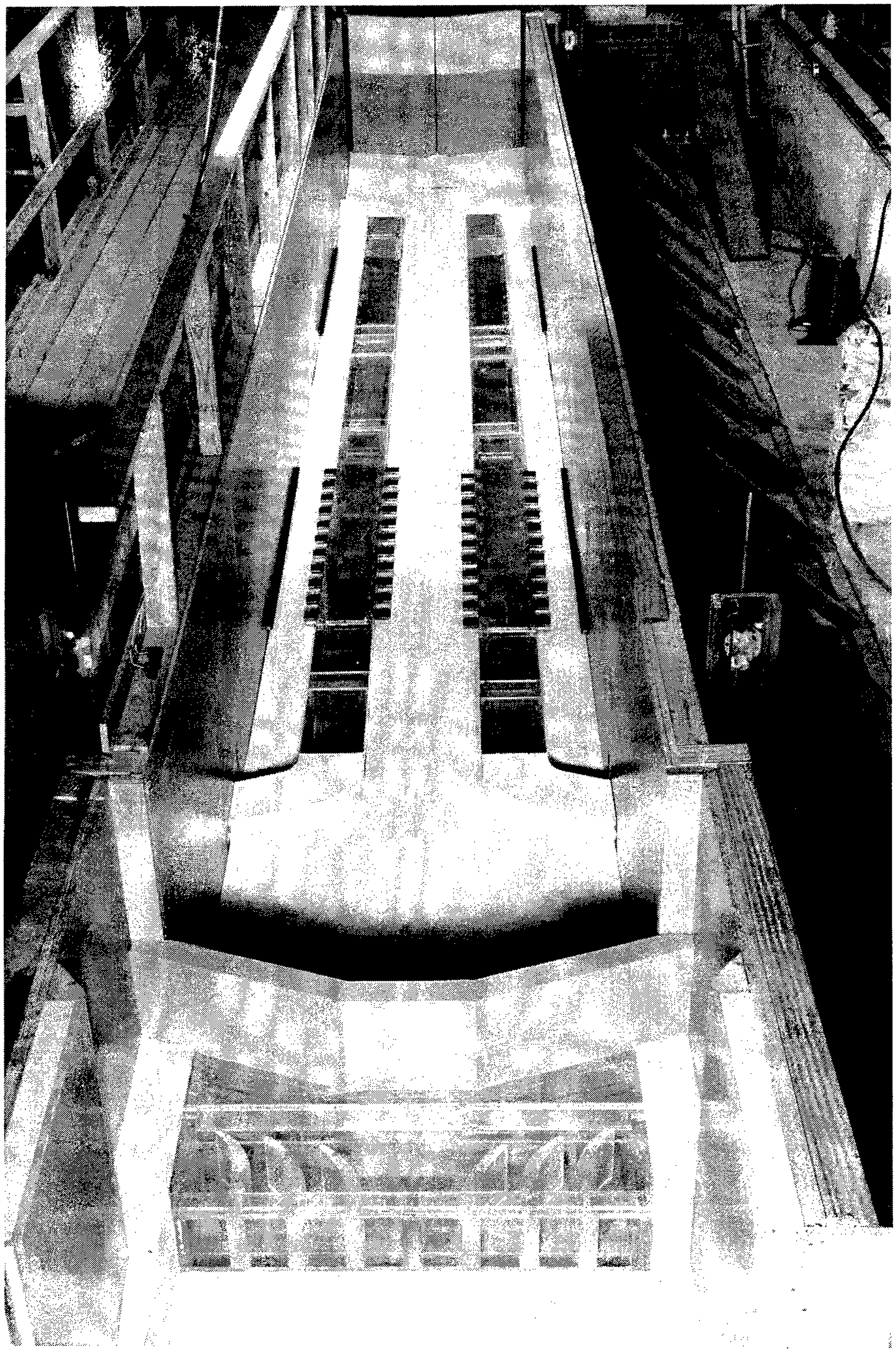


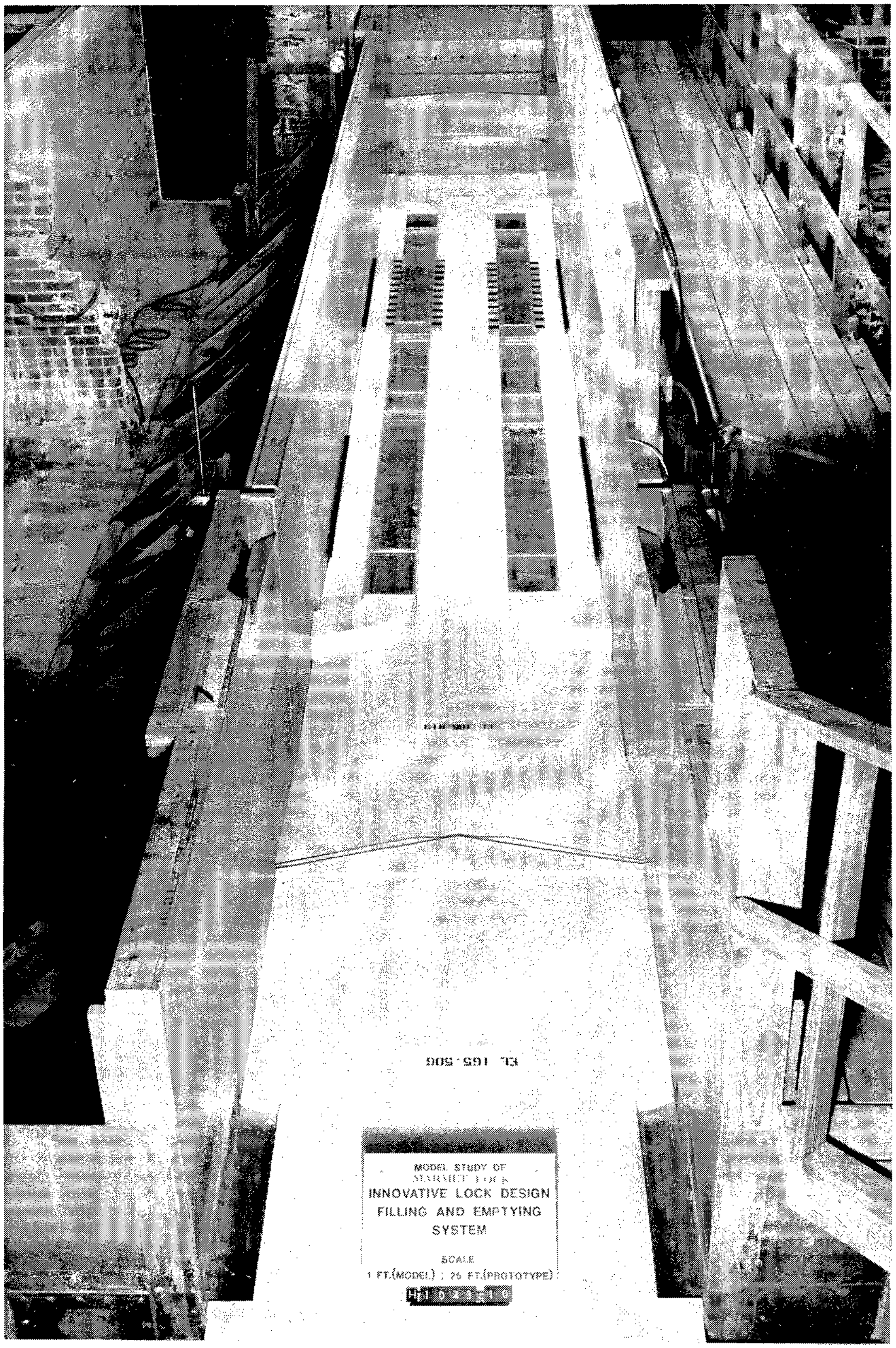
Figure 2. Dry bed view of Type 1 (original) design intake looking downstream

Figure 3. Side view of culvert between intake and filling valve, Type 1 design



a. Looking downstream

Figure 4. View of Type 1 filling and emptying system (Continued)



b. Looking upstream (lower miter gates removed)

Figure 4. (Concluded)

Figure 5. Emptying culvert valve well and discharge outlet manifold

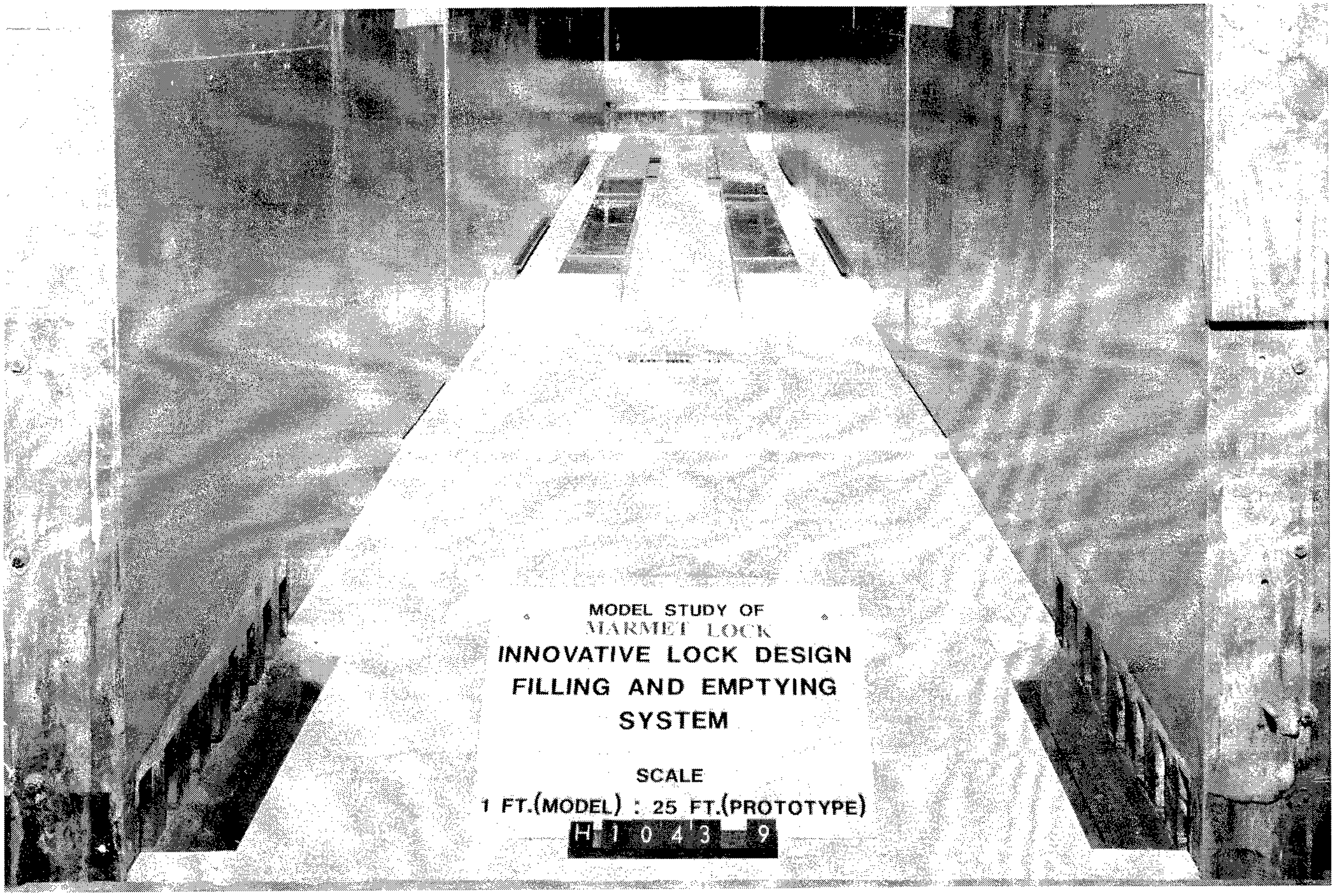


Figure 6. View of discharge outlet manifold looking upstream

Appurtenances and Instrumentation

Water was supplied to the model through a circulating system. Skimming weirs located in both the headbay and tailbay maintained essentially constant upper and lower pools during filling and emptying operations. Vertical adjustments of the skimming weirs permitted simulation of any desired upper and lower pool elevations. Dye and confetti were used to study subsurface and surface current directions. Pressure cells were used to measure instantaneous pressures in the culvert just downstream of the filling valve and to record water-surface elevation in the lock chamber. These pressure cells located within the chamber measured the water-surface variations in time at the upstream end, center, and downstream end. Histories of the end-to-end water-surface differential were also recorded during operations.

The movement of culvert valves was controlled by servo-driven linear actuators that were regulated by the output from a personal computer. Programming of the personal computer resulted in varied output such that the desired valve schedule could be reproduced.

A hawser-pull (force links) device used for measuring the longitudinal and transverse forces acting on a tow in the lock chamber during filling and emptying operations is shown in Figure 7. Three such devices were used: one measured longitudinal forces, and the other two measured transverse forces on the downstream and upstream ends of the tow, respectively. These links were machined from aluminum and had SR-4 strain gauges cemented to the inner and outer edges. When the device was mounted on the tow, one end of the link was pin-connected to the tow, while the other end was engaged to a fixed vertical rod. While connected to the tow, the link was free to move up and down with changes in the water-surface elevation in the lock. Any horizontal motion of the tow caused the links to deform and vary the signal, which was recorded with a personal computer using an analog-to-digital converter. The links were calibrated by inducing deflection with known weights. The strain gauge data used to determine hawser forces and the instantaneous pressure cell data were recorded digitally with a PC-based data acquisition system.

Pressures throughout the systems were measured with piezometers (open-air manometers). Pressures obtained in this manner are considered average pressures because of the reduction-in-frequency response resulting from the use of nylon tubing.

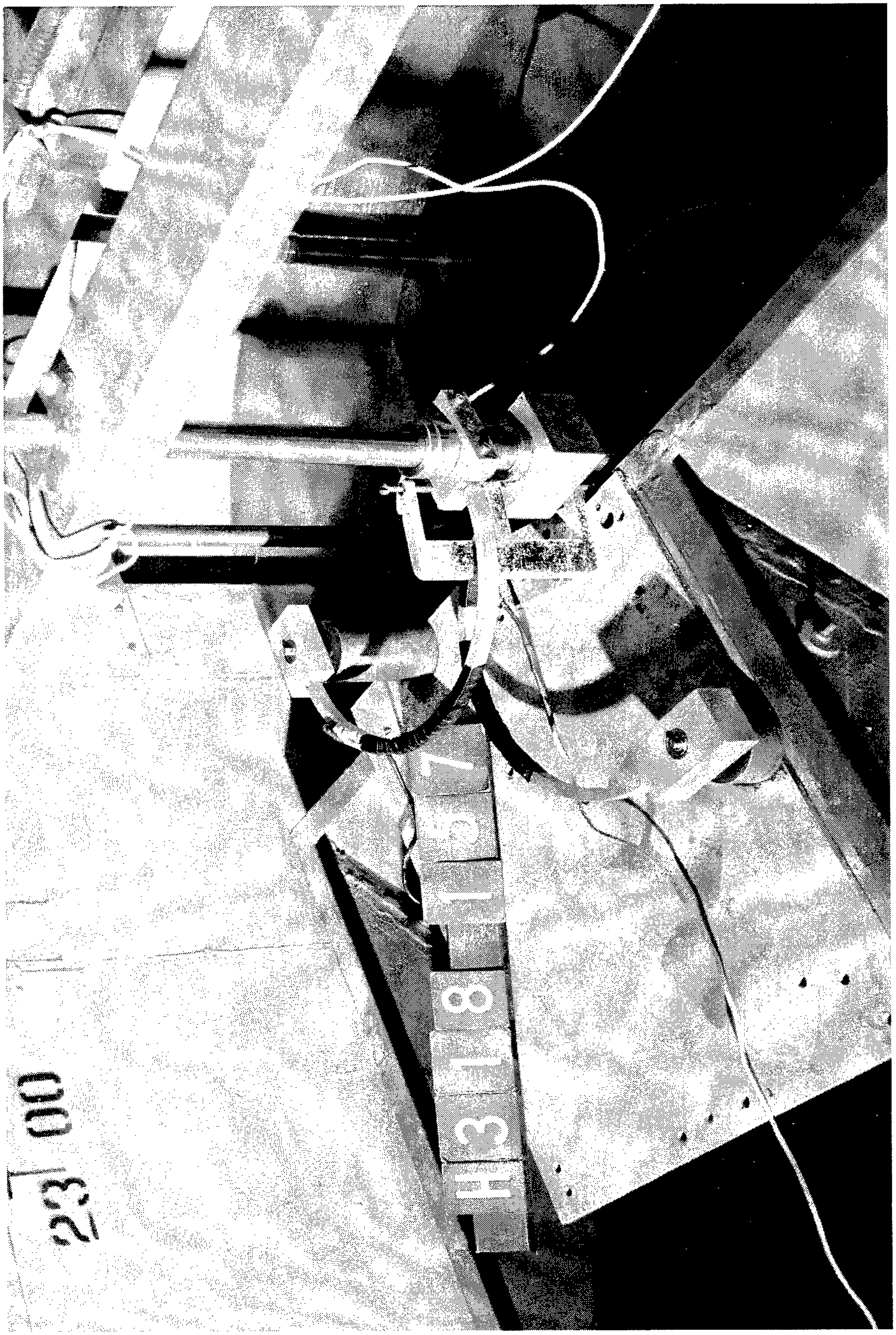


Figure 7. Hawser-pull (force links) measuring device

Similitude Considerations

Kinematic similitude

Kinematic similarity is an appropriate method of modeling free-surface flows in which the viscous stresses are negligible. Kinematic similitude requires that the ratios of inertial forces ($\rho V^2 L^2$) to gravitational forces ($\rho g L^3$) in the model are equal to those of the prototype. Here, ρ is the fluid density; V is the fluid velocity; L is a characteristic length, and g is the acceleration because of gravity. This ratio is generally expressed as the Froude number N_F.

$$N_F = \frac{V}{\sqrt{gL}} \tag{1}$$

where L, the characteristic length, is usually taken as the flow depth in open-channel flow.

The Froude number can be viewed in terms of the flow characteristics. Because a surface disturbance travels at celerity of a gravity wave $(gh)^{1/2}$, where h is the flow depth, one sees that the Froude number describes the ratio of advection speed to the gravity wave celerity. Evaluation of the lock chamber performance primarily concerns modeling of hawser forces on moored barges during filling and emptying operations. These hawser forces are generated primarily by slopes in the lock chamber water surface. The tow's bow-to-stern water-surface differentials are the result of long-period seiches in the lock chamber. Seiching is gravity waves traveling in the longitudinal direction from the upper miter gates to the lower miter gates. Equating Froude numbers in the model and prototype is an appropriate means of modeling the lock chamber.

Dynamic similitude

Modeling of forces is a significant purpose of the laboratory investigation. Appropriate scaling of viscous forces requires that the model be dynamically similar to the prototype. Dynamic similarity is accomplished when the ratios of the inertia forces to viscous forces (μVL) of the model and prototype are equal. Here, μ is the fluid viscosity. This ratio of inertia to viscous forces is usually expressed as

$$N_R = \frac{VL}{\nu} \tag{2}$$

the Reynolds number where ν is the kinematic viscosity of the fluid ($\nu = \mu/\rho$) and the pipe diameter is usually chosen as the characteristic length L in pressure-flow analysis.

Similitude for lock models

Numerous studies conducted to investigate vortex formation at intakes associated with critical submergence (generally defined as the submergence where an air-core vortex enters the intake) have indicated that the Froude number is an important parameter. The Froude number similarity is customarily used to model vortices, although corrections to model results are sometimes used to account for surface tension and viscous effects between the model and the prototype. Using a scale of 1 to 25 (model to prototype), as is the case for this lock model, minimizes the surface tension and viscous effects and provides acceptable results based on the Froude number similarity.

Complete similitude in a laboratory model is attained when geometric, kinematic, and dynamic similitude is satisfied. Physical models of hydraulic structures with both internal flow (pressure flow) and external flow (free surface) typically are scaled using kinematic (Froudian) similitude at a large enough scale so that the viscous effects in the scaled model can be neglected. More than 50 model and 10 prototype studies of lock filling and emptying systems have been investigated (Pickett and Neilson 1988). The majority of these physical model studies used a scale of 1 to 25 (model to prototype). Lock model velocities scaled using kinematic similitude (model Froude number equal to prototype Froude number) in a 1:25-scale model have maximum Reynolds numbers at peak discharges on the order of 10^5, yet the corresponding prototype values are on the order of 10^7.

Boundary friction losses in lock culverts are empirically described using the "smooth-pipe" curve of the Darcy-Weisbach friction factor where the head loss is expressed as

$$H_f = f \frac{L}{D} \frac{V^2}{2g} \tag{3}$$

where

H_f = head loss becuase of boundary friction

f = Darcy-Weisbach friction factor

L = culvert length

D = culvert diameter

The Darcy-Weisbach friction factor for turbulent flow in smooth pipes is given in an implicit form as (Vennard and Street 1982)

$$\frac{1}{\sqrt{f}} = 2.0\log\left(N_R\sqrt{f}\right) - 0.8 \tag{4}$$

Because f decreases with increasing N_R, the model is hydraulically "too rough." The scaled friction losses in the model will be larger than those experienced by the prototype structure. Consequently, the scaled velocities (and discharges) in the model will be less and the scaled pressures within the culverts will be higher than those of the prototype. Low pressures were not a particular concern with the Marmet design; however, the lower discharges would in turn result in longer filling and emptying times in the model than the prototype will experience. Prototype filling and emptying times for similar designs will be less than those measured in a 1:25-scale lock model.

Modeling of lock filling and emptying systems is not entirely quantitative. The system is composed of pressure-flow conduits and open-channel components. Further complicating matters, the flow is unsteady. Discharges (therefore N_F and N_R) vary from no flow at the beginning of an operation to peak flows within a few minutes and then return to no flow at the end of the cycle. Experience in conducting large-scale models and subsequently studying the corresponding prototype performance has shown that proper evaluation of model results provides valuable design information. This study used a 1:25-scale Froudian model in which the viscous differences were small and could be estimated based on previously reported model-to-prototype comparisons. Setting the model and prototype Froude numbers equal results in the following relations between the dimensions and hydraulic quantities:

Characteristic	**Dimension**[1]	**Scale Relation Model:Prototype**
Length	$L_r = L$	1:25
Pressure	$P_r = L_r$	1:25
Area	$A_r = L_r^2$	1:625
Velocity	$V_r = L_r^{1/2}$	1:5
Discharge	$Q_r = L_r^{5/2}$	1:3,125
Time	$T_r = L_r^{1/2}$	1:5
Force	$F_r = L_r^3$	1:15,625

[1] Dimensions are in terms of length.

These relations were used to transfer model data to prototype equivalents and vice versa.

Experimental Procedures

Evaluation of the various elements of the lock system was based on data obtained during typical filling and emptying operations. Performance was based primarily on hawser forces on tows in lockage, movement of unmoored (free) tows in the lock chamber, roughness of the water surface, pressures, and time required for filling and emptying. Quantification of energy-loss coefficients was made using fixed-head (steady-flow) conditions with the culvert valve and/or miter gates fully opened or closed.

3 Model Experiments and Results

Type 1 Design

Vortex experiments

The initial model experiments were performed to determine the lock approach flow conditions and the performance of the intake. Intakes placed in the miter gate sill are more prone to vortex formation than intakes located upstream and outside the lock approach walls. Vortex experiments were conducted by documenting the strength of vortices that formed in the upper approach for various valve operations. The strength of the vortex varies from a Type 1 vortex, which is a noticeable surface swirl, to a Type 6, which has an air-core that begins at the water surface and enters the intake. The vortex-strength classification used for the Marmet lock model experiments is shown in Plate 3 and was adopted from the Alden Research Laboratory (Padmanabhan and Hecker 1984) vortex-strength classification. Criteria based on kinematic and dynamic similitude for modeling vortices at this scale suggest that vortices that are Type 4 or stronger should be avoided. If a Type 4 vortex is observed in a model of this scale, a strong potential exists that the vortex will form in the prototype and will be even stronger. Vortices observed in the model that are a Type 3 or weaker are less likely to form strong vortices in the prototype.

Experiments were conducted by selecting the desired valve opening time with an upper pool el of 179.832 (590 ft) and a lower pool el of 172.517 (566 ft), which results in a lift of 7.315 m (24 ft). This lift was used for all experiments performed during the lock investigation. Vortex experiments were performed for 2-, 4-, and 8-min valve opening times. A minimum of 15 min (actual time) was allowed between each experiment to ensure that all currents generated from the previous experiment had ceased and experiments were repeated until the performance of the intake with that particular valve operation was established.

Two-minute valve speed. The results from experiments performed with the 2-min valve opening are provided in Table 1. Six experiments were conducted, and a Type 4 vortex was documented in five of the six experiments. The vortices usually formed as a result of the flow being drawn into the upper approach, contacting the miter gates that split the flow and directed it along the miter gates to the miter gate recess where it then turned in an upstream direction and began to move upstream. The flow circulated in the upper approach in the vicinity of the miter gate recesses and often intensified because of the flow drawn downward into the intake, and a Type 4 vortex formed. The strength often reduced in a matter of seconds in the model.

Four- and eight-minute valve speeds. Experiments were conducted next with the 4-min valve-opening time. The results from these experiments are listed in Table 2. The maximum strength vortex observed in the upper approach was a Type 3 and was observed in three of the six experiments. The maximum strength observed in the other three experiments was a Type 2. Flow conditions in the upper approach were improved over those observed with the 2-min valve operation. The flow circulation was not as concentrated, and the vortex strength was less. Results from the vortex experiments conducted with the 8-min valve are provided in Table 3. A Type 2 vortex formed in one of the six experiments, and the maximum strength observed in the other five experiments was a Type 1. Flow conditions in the upper approach with the 8-min valve operation were considered calm.

Free tow experiments

Free tow experiments were conducted next to help evaluate the performance of the filling and emptying system. An unmoored three-wide-by four-long-barge arrangement was placed in the lock chamber as shown in Plate 4, and filling and emptying operations were conducted with various valve speeds. Longitudinal drift patterns were recorded and plotted to illustrate the movement of the barges during filling and emptying. A track of the barge movement during filling and emptying with the 2-min valve is shown in Plate 5. The barges began drifting slightly towards the downstream miter when the flow started to enter the lock chamber; about 3.5 min into the filling operation, the barges reversed directions and moved towards the upstream miter. Contact was made with the upstream miter just after 8 min. The lock reached the upper pool el around 7.6 min. Once the barges began moving, sufficient momentum was achieved to impact the upstream miter gate even after the lock chamber was filled. During emptying with the 2-min valve, the barges began to drift slowly towards the downstream miter gate, but no contact was made.

Free tow longitudinal drift patterns during filling and emptying for 3-, 4-, and 8-min valve operations are shown in Plates 6-8. Impact with the downstream miter occurred with the 4- and 8- min valves during emptying. The barges began drifting slowly towards the downstream miter gate,

Table 1
Intake Vortex Experiments, Original Design, Without Trash Racks, 2-Min Valve (Upper Pool El 179.832, Lower Pool El 172.517)

Vortex Strength	Prototype Time, min	Vortex Strength	Prototype Time, min
Experiment No. 1		**Experiment No. 3**	
1	2.50	1	2.33
2	3.08	2	2.67
3	3.75	3	3.17
2	7.50	4	3.42
1	8.33	3	3.67
0	10.00	4	4.17
Experiment No. 2		3	4.67
1	2.50	2	5.42
2	2.92	1	7.50
3	3.33	0	8.75
2	3.75	**Experiment No. 4**	
3	4.50	1	2.08
4	5.00	2	2.50
3	5.67	3	2.75
2	5.92	2	3.50
1	7.92	3	3.75
0	8.75	4	3.92
		3	4.25
		2	5.00
		3	5.33
		2	5.67
		1	7.08
		0	8.75

(Continued)

Table 1 (Concluded)

Vortex Strength	Prototype Time, min	Vortex Strength	Prototype Time, min
Experiment No. 5		**Experiment No. 6**	
1	2.25	1	2.25
2	2.75	2	2.75
3	2.95	3	3.00
2	3.33	4	3.25
3	3.92	3	3.42
2	4.75	4	4.00
3	5.00	3	4.67
4	5.42	2	5.42
3	5.83	1	7.08
2	6.67	0	8.33
1	7.50		
0	9.17		

Table 2
Intake Vortex Experiments, Original Design, Without Trash Racks, 4-Min Valve (Upper Pool El 179.832, Lower Pool El 172.517)

Vortex Strength	Prototype Time, min	Vortex Strength	Prototype Time, min
Experiment No. 1		**Experiment No. 4**	
1	3.75	1	3.58
2	4.17	2	3.83
1	7.92	1	6.25
0	9.58	2	7.08
Experiment No. 2		1	7.50
1	3.50	0	9.17
2	4.17	**Experiment No. 5**	
1	7.92	1	3.75
0	9.17	2	4.58
Experiment No. 3		3	5.83
1	4.58	2	6.67
2	5.00	1	7.50
3	5.25	0	9.58
2	6.25	**Experiment No. 6**	
1	7.08	1	3.58
0	9.17	2	3.83
		3	4.17
		2	4.83
		1	7.08
		0	9.17

Table 3
Intake Vortex Experiments, Original Design, Without Trash Racks, 8-Min Valve (Upper Pool El 179.832, Lower Pool El 172.517)

Vortex Strength	Prototype Time, min	Vortex Strength	Prototype Time, min
Experiment No. 1		**Experiment No. 4**	
1	6.08	1	5.00
0	10.42	0	11.25
Experiment No. 2		**Experiment No. 5**	
1	5.92	1	5.83
0	7.50	0	11.67
1	10.00	**Experiment No. 6**	
0	10.83	1	1.17
Experiment No. 3		2	5.83
1	5.00	1	7.08
0	11.67	2	8.33
		1	9.08
		0	11.67

and contact occurred approximately 8 min after the filling operation started with the 4-min valve and 9 min after the filling operation started with the 8-min valve. This type movement indicates that there were no rapid accelerations. Results of the free tow drift patterns indicated the performance of the original design filling and emptying was good enough to proceed with the hawser measurements without modifying the system.

Hawser force measurements

Experiments were conducted next to measure hawser forces for a three- by four-barge arrangement secured inside the barge chamber. The hawser-pull (force links) device, discussed previously, used for measuring the longitudinal and transverse forces on a tow in the lock chamber during the filling and emptying operations is shown in Figure 7.

Filling operations

Longitudinal hawser forces, 2-min valve. Results from a typical experiment with the 2-min valve operation are shown in Plate 9. Time histories of the upstream and downstream longitudinal and transverse hawser forces are shown along with the piezometric head measured 2.25 m (7.38 ft, which is one-half the culvert height) downstream of the left filling valve. The lock water-surface elevation is also shown and was determined by averaging the piezometric head from pressure cells mounted in the middle and on both ends of the lock. The longitudinal hawsers indicate that immediately after the valve begins to open, the barges inside the lock experience an upstream hawser force for a few seconds and then begin to experience a downstream hawser force that generally was the maximum hawser force experienced during the filling operation. Between 1 and 2 min into the filling cycle, the longitudinal hawser force changes from downstream to upstream, and the maximum upstream hawser force was experienced around 1.5 min into the filling operation. The longitudinal hawser force then begins to fluctuate between downstream and upstream direction, and the magnitude is greatly reduced.

Hawser forces measured with the original design filling and emptying system with an upper pool el of 179.832 (590 ft) and a lower pool el of 172.517 (566 ft) for 2-, 4-, and 8-min valves are shown in Plate 10. The hawser measurements and filling times shown are the average value computed from several experiments. Experiments were repeated to ensure consistency. The average of the maximum longitudinal hawser forces measured with the 2-min valve was 88.05 kN (9.9 tons) in the downstream direction and 62.28 kN (7.0 tons) in the upstream direction. These longitudinal hawser forces were slightly higher than the 5.0-ton limit suggested by Corps of Engineers' design guidance.

Transverse hawser forces, 2-min valve. Transverse hawser forces measured for a typical experiment with a 2-min valve operation are shown in Plate 9. The transverse forces fluctuate regularly from side to side (right to left) with the largest magnitudes occurring between 2 and 4 min into the filling cycle. These magnitudes were less than the longitudinal hawser forces. The average of the maximum transverse hawser forces measured with the 2-min valve on the upstream end of the lock chamber was 38.25 kN (4.3 tons) on the right side, looking downstream, and 43.59 kN (4.9 tons) on the left side. In this report, right and left directions are always referenced to looking downstream. The average of the maximum transverse hawser forces measured with the 2-min valve on the downstream end of the lock chamber was 33.81 kN (3.8 tons) on the right side and 40.03 kN (4.5 tons) on the left side.

Longitudinal and transverse hawser forces, 4-min valve. Results from a typical experiment with the 4-min valve operation with the 7.315-m (24-ft) lift are shown in Plate 11. The temporal variation of the longitudinal hawser forces was similar to those measured with the 2-min valve except the magnitudes were less. The average of the maximum

longitudinal hawser forces measured with the 4-min valve was 56.05 kN (6.3 tons) in the downstream direction and 40.03 kN (4.5 tons) in the upstream direction. The average of the maximum transverse hawser forces measured on the upstream end of the lock valve was 16.01 kN (1.8 tons) on the right side and 30.25 kN (3.4 tons) on the left side. The average of the maximum transverse hawser forces measured on the downstream end of the lock valve was 13.34 kN (1.5 tons) on the right side and 27.58 kN (3.1 tons) on the left side. These hawser forces were considered marginally acceptable since the maximum hawser force measured was very close to the 44.48-kN (5.0-ton) limit suggested in the Corps' design guidance. The average maximum longitudinal and transverse hawser forces are shown in Plate 10.

Longitudinal and transverse hawser forces, 8-min valve. Results from a typical experiment with the 8-min valve operation with the lift of 7.315 m (24 ft) are shown in Plate 12. The average of the maximum longitudinal hawser forces measured with the 8-min valve was 33.81 kN (3.8 tons) in the downstream direction and 28.47 kN (3.2 tons) in the upstream direction. The temporal variation in the longitudinal hawser was similar to those measured with the 2- and 4-min valve operations, and the magnitudes were less than those measured with the 4-min valve. The average of the maximum transverse hawser forces measured with the 8-min valve on the upstream end of the lock was 10.68 kN (1.2 tons) on the right side and 20.46 kN (2.3 tons) on the left side. The average of the maximum transverse hawser forces measured with the 8-min valve on the downstream end of the lock was 11.57 kN (1.3 tons) on the right side and 14.23 kN (1.6 tons) on the left side.

Emptying operations

Hawser force measurements and emptying times were also determined with 2-, 4-, and 8-min valve operations with the 7.315-m (24-ft) lift. The averages of the maximum longitudinal and transverse hawser forces measured for these valve schedules are shown in Plate 13. Both longitudinal and transverse hawser forces were less than those measured during filling operations (one should compare Plates 10 and 13).

Filling times

Filling time, 2-min valve. As mentioned previously, the lock water-surface elevation was determined during the filling operation by averaging the piezometric head recorded by pressure cells mounted in the middle and on both ends of the lock. The filling curve determined for the original design for a typical experiment with an upper pool el of 179.832 (590 ft), a lower pool el of 172.517 (566 ft), and a 2-min valve-opening operation for a typical experiment is shown in Plate 9 along with the hawser data. The average filling time with the 2-min valve operation determined from several experiments is shown Plate 14 along with the average

filling time determined with 4- and 8-min valve schedules. The average filling time with the 2-min valve opening was 7.6 min.

Filling time, 4-min valve. The average filling time determined for the original design with an upper pool el of 179.832 (590 ft), a lower pool el of 172.517 (566 ft), and a 4-min valve-opening operation was 8.4 min.

Filling time, 8-min valve. The average filling time determined for the original design with an upper pool el of 179.832 (590 ft), a lower pool el of 172.517 (566 ft), and an 8-min valve-opening operation was 10.3 min.

Emptying times

The emptying times for the 2-, 4-, and 8-min valve operations with an upper pool el of 179.832 (590 ft) and a lower pool el of 172.517 (566 ft) were 7.4, 8.4, and 10.3 min, respectively.

The performance of the original design lock filling and emptying system was acceptable for operations with valve speeds slower than 4 min. The maximum strength vortex that formed with a 4-min valve was a Type 3, and the maximum hawser forces were acceptable.

Type 3 Approach Design

The approach topography was modified to try and improve the approach flow conditions and reduce the strength of the vortices during filling operations. Flow was not well distributed, depthwise, with the original design, and the flow concentrations tended to increase the strength of the vortices. The flow concentrations resulted from flow separating as it passed over the bulkhead sill creating an elevation view roller below the sill and interacting with a plan view eddy that formed in the miter gate recess from the flow being redirected as it impacted the miter gates. The stronger vortices generally formed in the vicinity of the upstream end of the right miter gate recess. Vortices were also observed near the left miter gate recess, but these were not as strong.

Modifications to the upper approach were discussed with the Huntington District. The Type 2 design shown in Plate 15 was developed to distribute the flow better, but was rejected since major modifications to the bulkhead were required with this design. The Type 3 approach design shown in Plate 16 was adopted since it required less changes to the bulkhead sill. This design consisted of lowering the bulkhead sill crest el from 170.385 (559 ft) to 169.166 (555 ft) and placing a 6.096-m (20-ft) radius between the bulkhead sill and a 1V on 1.5 H downslope that extended to the floor of the approach. A fillet was also placed just upstream of the intake between the floor and the intake to improve the entrance flow.

Vortex experiments were performed to help evaluate the approach flow conditions with 2-, 4-, and 8-min valve operations. Results of the experiments performed with the 2-min valve are provided in Table 4. The maximum strength vortex was a Type 3, which was less than with the original design. The maximum strength vortex that formed with the 4-min valve (Table 5) was also a Type 3. The maximum strength vortex observed with the 8-min valve (Table 6) was also a Type 3, but occurred in only one of the six experiments. This strength vortex (a Type 3) is generally considered the strongest allowed in model experiments at this scale. The upper approach flow conditions were improved with the Type 3 design approach. Flow was distributed more uniformly in the approach, and the strength of the vortices was reduced. The Type 3 approach topography was an improvement from the original design.

Type 4 Approach Design

Experiments were performed next to determine the effect that a roof extension (placed as shown in Plate 17) had on vortex formation during filling operations. The roof extension with the Type 3 approach was designated the Type 4 approach design. Vortex experiments were performed for 2-, 4-, and 8-min valve schedules. The results from these experiments are provided in Tables 7-9. The maximum strength vortex that formed in five of the six experiments with a 2-min valve was a Type 2. A Type 3 vortex formed in one experiment. The maximum strength vortex that formed with the 4- and 8-min valve operations was a Type 2. A comparison of vortex strength during representative experiments with the original design and the Types 3 and 4 approach designs is shown in Plate 18 for the 2-min valve. Vortex strength was less with the Type 4 design approach, indicating better approach flow conditions. Since conditions with the Type 3 approach were also satisfactory, this design was in place for the remaining experiments.

Type 2 Chamber Design

Modifications to the lock chamber were made next to try and reduce the hawser forces with the 2-min valve operation. Hawser forces less than 44.48 kN (5 tons) were desired. A baffle 0.610 m (2 ft) high by 0.610 m (2 ft) wide was installed in front of the port extensions in the upstream half of the chamber as shown in Plate 19. This modification was designated the Type 2 chamber design. Hawser force experiments were performed during filling with the 7.315-m (24-ft) lift and a 2-min valve operation. The average of the maximum hawsers measured for the experiments conducted with the Type 2 chamber design is shown in Plate 20. The average maximum longitudinal downstream hawser force was 101.42 kN (11.4 tons), and the average maximum upstream hawser force

Table 4
Intake Vortex Experiments, Type 3 Design Approach, 2-Min Valve (Upper Pool El 179.832, Lower Pool El 172.517)

Vortex Strength	Prototype Time, min	Vortex Strength	Prototype Time, min
Experiment No. 1		**Experiment No. 4**	
1	2.75	1	2.75
2	3.08	2	3.08
3	3.42	3	3.33
2	3.83	2	4.17
1	5.83	3	4.83
0	7.50	2	5.00
Experiment No. 2		1	6.25
1	2.67	0	7.50
2	2.92	**Experiment No. 5**	
3	3.08	1	2.83
2	4.17	2	3.33
1	6.25	3	3.50
0	7.50	2	4.17
Experiment No. 3		1	5.83
1	2.92	0	7.50
2	3.17	**Experiment No. 6**	
3	3.50	1	2.75
2	4.42	2	3.00
1	5.83	3	3.33
0	7.50	2	3.75
		1	4.58
		2	5.00
		1	5.67
		0	7.08

Table 5
Intake Vortex Experiments, Type 3 Design Approach, 4-Min Valve (Upper Pool El 179.832, Lower Pool El 172.517)

Vortex Strength	Prototype Time, min	Vortex Strength	Prototype Time, min
Experiment No. 1		**Experiment No. 4**	
1	4.17	1	4.17
2	4.42	2	4.42
3	5.00	3	5.00
2	5.42	2	5.33
1	6.25	1	6.67
0	8.75	0	8.33
Experiment No. 2		**Experiment No. 5**	
1	4.17	1	4.00
2	4.58	2	4.17
3	6.25	3	4.58
2	6.67	2	5.00
1	7.50	1	7.08
0	8.33	0	8.75
Experiment No. 3		**Experiment No. 6**	
1	4.33	1	3.75
2	4.67	2	4.17
3	5.08	3	4.58
2	5.83	2	6.08
1	7.08	1	6.67
0	8.75	0	7.92

Table 6
Intake Vortex Experiments, Type 3 Design Approach, 8-Min Valve (Upper Pool El 179.832, Lower Pool El 172.517)

Vortex Strength	Prototype Time, min	Vortex Strength	Prototype Time, min
Experiment No. 1		**Experiment No. 4**	
1	5.83	1	5.00
2	6.92	2	6.25
1	9.17	1	8.33
0	10.00	1	10.83
Experiment No. 2		**Experiment No. 5**	
1	5.83	1	5.83
2	6.25	2	8.33
1	7.08	1	9.17
2	8.17	0	10.00
3	8.75	**Experiment No. 6**	
2	9.17	1	5.83
1	9.58	0	11.67
0	10.00		
Experiment No. 3			
1	6.25		
0	10.00		

Table 7
Intake Vortex Experiments, Type 4 Design Approach, 2-Min Valve (Upper Pool El 179.832, Lower Pool El 172.517)

Vortex Strength	Prototype Time, min	Vortex Strength	Prototype Time, min
Experiment No. 1		**Experiment No. 4**	
1	2.50	1	3.75
0	2.92	2	5.00
1	3.92	1	5.83
2	4.17	0	11.67
1	4.67	**Experiment No. 5**	
2	5.83	1	3.50
1	6.67	2	3.92
0	8.33	1	4.58
Experiment No. 2		0	7.50
1	3.83	**Experiment No. 6**	
2	4.08	1	3.33
3	4.67	2	3.50
2	5.00	1	3.75
1	5.83	2	5.00
0	7.92	1	5.25
Experiment No. 3		0	8.33
1	3.75		
2	4.17		
1	5.83		
0	8.33		

Table 8
Intake Vortex Experiments, Type 4 Design Approach, 4-Min Valve (Upper Pool El 179.832, Lower Pool El 172.517)

Vortex Strength	Prototype Time, min	Vortex Strength	Prototype Time, min
Experiment No. 1		Experiment No. 4	
1	6.25	1	6.67
2	6.42	0	6.92
1	6.58	1	7.92
0	10.00	0	8.17
Experiment No. 2		Experiment No. 5	
1	6.92	1	5.00
0	7.33	2	5.42
Experiment No. 3		1	5.83
1	5.00	0	8.33
2	5.42	Experiment No. 6	
1	6.25	1	7.92
0	8.75	0	8.33

Table 9
Intake Vortex Experiments, Type 4 Design Approach, 8-Min Valve (Upper Pool El 179.832, Lower Pool El 172.517)

Vortex Strength	Prototype Time, min	Vortex Strength	Prototype Time, min
Experiment No. 1		Experiment No. 4	
1	4.58	1	8.33
0	5.00	0	9.17
1	6.25	Experiment No. 5	
2	6.67	1	7.50
1	7.08	2	8.75
0	7.92	1	9.17
Experiment No. 2		0	10.00
0	0.00	Experiment No. 6	
0	10.00	1	8.75
Experiment No. 3		0	10.42
1	7.08		
0	8.33		

was 21.35 kN (2.4 tons). The average maximum transverse hawser forces measured with the 2-min valve on the upstream end of the lock were 29.36 kN (3.3 tons) on the right side and 35.59 kN (4.0 tons) on the left side. The average maximum transverse hawser forces measured with the 2-min valve on the downstream end of the lock was 24.02 kN (2.7 tons) on the right side and 33.81 kN (3.8 tons) on the left side. The average maximum downstream longitudinal hawser force increased form 88.07 kN (9.9 tons) with the original design to 101.42 kN (11.4 tons) with the Type 2 chamber design; therefore, this design was modified.

Hawser forces were also measured during the emptying operations with a 2-min valve schedule to determine if any changes from the original design occurred with the Type 2 chamber design. The average maximum longitudinal and transverse hawser forces for the Type 2 chamber design with the 2-min valve are shown in Plate 21. The upstream longitudinal hawser forces were slightly higher with the Type 2 chamber design compared with the original design, and the transverse hawser forces were very similar to the forces measured with the original design.

Type 3 Chamber Design

The baffle walls were removed from the ports adjacent to the lock walls in the upstream half of the chamber as shown in Plate 19. This design was designated the Type 3 chamber design, and results of the hawser force measurements made during filling are provided in Plate 20. The average maximum longitudinal downstream hawser force was 95.19 kN (10.7 tons), and the average maximum upstream hawser force was 36.48 kN (4.1 tons). The average maximum transverse hawser forces measured with the 2-min valve on the upstream end of the lock was 36.48 kN (4.1 tons) on the right side and 35.59 kN (4.0 tons) on the left side. The average maximum transverse hawser forces measured with the 2-min valve on the downstream end of the lock was 27.58 kN (3.1 tons) on the right side and 47.15 kN (5.3 tons) on the left side. The maximum longitudinal downstream hawser force was reduced from the Type 2 chamber design, but was still higher than the original design. Hawser forces during emptying operations with the 2-min valve are shown in Plate 21. The transverse hawser forces did not change significantly from the Type 2 chamber design, so additional modifications were continued.

Type 4 Chamber Design

Since the baffle walls were not improving chamber performance with the 2-min valve operation, a different concept was employed. The experiments with the Types 2 and 3 chamber designs indicated higher hawser forces were occurring in the downstream direction. The Type 4 chamber

design consisted of increasing the throat length of the first six upstream ports by 2.591 m (8.5 ft) as shown in Plate 22 instead of placing additional baffles in the chamber. The average maximum longitudinal downstream hawser force measured with the Type 4 chamber design and the 2-min valve was 83.63 kN (9.4 tons). The average maximum longitudinal upstream hawser force was 72.06 kN (8.1 tons). The average maximum transverse hawser forces measured with the 2-min valve on the upstream end of the lock was 24.02 kN (2.7 tons) on the right side and 43.59 kN (4.9 tons) on the left side. The average maximum transverse hawser forces measured with the 2-min valve on the downstream end of the lock was 24.02 kN (2.7 tons) on the right side and 40.03 kN (4.5 tons) on the left side. The longitudinal hawsers were more balanced with this design; however, there was no significant change from the original design. The hawser forces measured during emptying operations (shown in Plate 21) with the Type 4 chamber design also indicated there were no significant reductions in the hawser forces.

The experiments performed with the Types 2-4 chamber designs indicated that these minor changes to the baffle arrangements and port throat length did not have much effect on the magnitude of the hawser forces. Since the original design was developed to operate with a 4-min valve and the chamber performance was acceptable with this valve operation, no further experiments were performed to improve the performance with the 2-min valve.

Velocities in the Upper Approach

Velocities were measured in the upper approach with a normal upper pool el of 179.832 (590 ft), a 4-min valve operation, the Type 3 approach design, and the original design filling and emptying system. The velocity probe was placed at selected locations 2.74 m (9 ft) beneath the surface. The output from the probe was monitored during lock filling with a 4-min valve, and the maximum velocity observed during the cycle was recorded. Along the right half of the upper approach, the velocities ranged from 0.27 m/sec (0.9 ft/sec) near the guard wall 190.020 m (525 ft) upstream from the pintle to 0.70 m/sec (2.3 ft/sec) in the center of the bulkhead sill, 38.100 m (125 ft) upstream from the pintle as shown in Plate 23. The highest velocity, 1.01 m/sec (3.3 ft/sec), occurred just downstream from the bullnose on the left side of the approach. This was the area where flow was drawn around the bullnose. These velocities measured were not considered excessive.

Type 1 Discharge Manifold

The design of the Type 1 manifold for the Marmet lock outlet was based on an outlet manifold design used for the Red River projects. This design, investigated by Stockstill (1990), provided acceptable flow distributions when evaluated with steady discharges. The flow conditions in the lower lock approach of Marmet lock with the Type 1 discharge manifold were evaluated by measuring the bulking of the water surface during 2-, 4-, and 8-min valve-emptying operations and recording the maximum velocities at selected locations during these emptying operations. The maximum rise in water surface versus emptying-valve operation is shown in Plate 24, and the location where this measurement was made is shown in Plate 25 along with the maximum velocities measured during an emptying operation with a 2-min valve. The velocity measurements were obtained 2.743 m (9 ft) below the normal lower pool el of 172.517 m (566 ft). A maximum velocity of 1.55 m/sec (5.1 ft/sec) was measured in the lower approach with the 2-min valve-emptying operation. The maximum velocity measured with the 4-min emptying operation was 1.52 m/sec (5.0 ft/sec), Plate 26, and the maximum velocity measured with the 8-min valve-emptying operation was 1.07 m/sec (3.5 ft/sec) as shown in Plate 27.

Pressure Measurements

Instantaneous pressures were measured with pressure cells mounted on the roof of the culvert downstream from the left filling valve (Sta 0+22.87 B, Plate 28) and also downstream from the left emptying valve at Sta 2+42.91 B. High velocities that occur with partial gate openings can cause low pressures downstream of the valve, which, if low enough, can result in cavitation damage. Time histories of the pressure just downstream of the filling valves for typical filling operations with 2-, 4-, and 8-min valve times are shown in Plates 29-31. The culvert roof elevation downstream from the filling valve was 168.118 m (551.60 ft). The pressures measured downstream of the valve indicate the pressure is above the roof elevation for the 2-, 4-, and 8-min filling-valve operations with the 7.31-m (24-ft) lift.

Time histories of the pressure just downstream of the emptying valves for typical emptying operations with 2-, 4-, and 8-min valve times are shown in Plates 32-34. The culvert roof elevation downstream from the emptying valve was 166.957 m (547.79 ft). The pressures measured downstream of the valve indicate that the pressure is also above the roof elevation for the 2-, 4-, and 8-min emptying-valve operations with the 7.31-m (24-ft) lift.

Pressures were also measured using piezometers placed at the locations in the system shown in Plate 28. The minimum piezometric pressures and

locations recorded during filling and emptying operations with 2-, 4-, and 8-min operations are shown in the following tabulation.

Minimum Piezometric Pressures with Upper Pool El 179.832 (590 ft) and Lower Pool El 172.517 (566 ft)						
Valve Operation	**Valve Time min**	**Piezometer**	**Piezometer El**	**Piezometer Reading, m**	**Culvert Roof El**	**Time of Reading sec**
Filling	2	SC 5	164.707	170.993	166.957	24
Emptying	2	SC 7	164.707	169.865	166.957	26
Filling	4	SC 3	165.213	172.090	167.463	17
Emptying	4	SC 7	164.707	169.987	166.957	50
Filling	8	SC 3	165.213	172.151	167.463	26
Emptying	8	SC 7	164.707	171.663	166.957	86

The experimental results showed the Type 1 chamber design provided positive head during filling and emptying operations.

Piezometer readings were also obtained during experiments with steady flows conducted to help evaluate the losses throughout the system. The lowest piezometer reading observed with a steady flow of 10,800 cfs,[1] an upper pool el of 179.710 (589.6 ft), a lower pool el of 172.212 (565.0 ft), the emptying valves closed, and the lower miter gates open occurred at piezometer SC 1 and was 169.225 m (555.2 ft). This is 0.610 m (2 ft) above the roof el and indicated the piezometric pressure also remained positive during these conditions.

The pressure measurements obtained throughout the filling and emptying system during steady-flow conditions were used to determine the head losses for the system components. The energy loss through each component can be expressed

$$H_{L_i} = K_i \frac{V^2}{2g} \tag{5}$$

where

K_i = loss coefficient for component i

1 To convert cubic feet per second to cubic meters per second, multiple by 0.02831685.

V = culvert velocity, which is one-half total discharge divided by culvert area of 4.000 m (13.12 ft) by 5.500 m (14. 76 ft)

The total head loss through the system is

$$H_L = \sum H_{L_i} = \sum K_i \frac{V^2}{2g} \tag{6}$$

The lock coefficient is defined as

$$C_L = \frac{V}{\sqrt{2gH_L}} \tag{7}$$

Equating the head loss H_L in each expression shows the relation between the lock coefficient and loss coefficient.

$$K = C_L^{-2} \quad or \quad C_L = K^{-0.5} \tag{8}$$

where K is the sum of each K_i. The total energy loss coefficient for the filling system K was determined to be 2.1. The following tabulation provides the values for the components, and the sum is the total energy loss coefficient.

Component	Loss Coefficient, K_i
Intake, valves, and three bends	0.7
Culvert upstream of manifold	0.1
Manifold	1.3

The overall lock coefficient was determined to be 0.69. This coefficient is similar to that determined for the McAlpine Lock model in-chamber longitudinal filling and emptying system (Stockstill 1998).

Modified Miter Gate Shape

The shape of the upstream miter gate was corrected to represent the mitered shape rather than the blunt shape at the miter sill and additional vortex experiments were performed. The results of these experiments are provided in Tables 10-12. Six experiments were conducted with the 2-min valve operation, and a Type 4 vortex was documented in two of the six experiments. The flow conditions in the upper approach were not noticeably changed with the corrected miter shape in the model. Experiments conducted with the 4- and 8-min valve operations were similar to

Table 10
Intake Vortex Experiments, Type 3 Design Approach, Corrected Upstream Miter Shape, 2-Min Valve (Upper Pool El 179.832, Lower Pool El 172.517)

Vortex Strength	Prototype Time, min	Vortex Strength	Prototype Time, min
Experiment No. 1		**Experiment No. 4**	
1	2.75	1	3.17
2	3.00	2	3.50
3	3.42	3	3.75
2	3.67	4	4.17
1	5.83	3	4.25
0	7.50	2	4.42
Experiment No. 2		1	6.67
1	2.50	0	7.50
2	3.08	**Experiment No. 5**	
3	3.42	1	2.92
2	4.17	2	3.17
1	5.42	3	3.33
0	7.50	2	3.75
Experiment No. 3		1	6.67
1	3.00	0	7.50
2	3.17	**Experiment No. 6**	
3	3.50	1	2.75
2	3.75	2	3.08
1	7.92	3	3.33
0	8.33	4	3.50
		3	3.75
		2	4.42
		1	5.42
		0	6.67

Table 11
Intake Vortex Experiments, Type 3 Design Approach, Corrected Upstream Miter Shape, 4-Min Valve (Upper Pool El 179.832, Lower Pool El 172.517)

Vortex Strength	Prototype Time, min	Vortex Strength	Prototype Time, min
Experiment No. 1		**Experiment No. 4**	
1	5.42	1	3.75
0	5.83	2	4.58
Experiment No. 2		1	5.42
1	4.42	0	8.33
2	5.42	**Experiment No. 5**	
1	6.25	1	4.58
0	8.33	0	8.33
Experiment No. 3		**Experiment No. 6**	
1	4.58	1	4.33
0	5.83	2	5.42
1	6.67	1	5.83
0	8.33	0	8.33

Table 12
Intake Vortex Experiments, Type 3 Design Approach, Corrected Upstream Miter Shape, 8-Min Valve (Upper Pool El 179.832, Lower Pool El 172.517)

Vortex Strength	Prototype Time, min	Vortex Strength	Prototype Time, min
Experiment No. 1		Experiment No. 4	
1	5.83	1	7.50
2	6.08	2	7.92
1	7.08	1	8.33
2	7.50	0	10.00
1	9.17	Experiment No. 5	
0	10.00	1	6.67
Experiment No. 2		2	7.50
1	7.50	1	8.75
0	7.92	0	10.42
Experiment No. 3		Experiment No. 6	
1	5.83	1	6.75
2	6.25	0	6.67
1	7.08	1	8.33
0	10.00	0	10.00

those conducted previously with the Type 3 approach topography. The maximum strength vortex observed in the upper approach was a Type 2 during these valve operations. The results from these experiments revealed there were no significant changes in the strength of the vortices observed from those with the previous blunt-shape miter gate.

Raised Floor Experiment

Further design work performed by the Huntington District indicated that construction savings would be realized if the floor of the lock chamber could be raised. A qualitative experiment was performed to investigate the effect of raising the lock floor by 0.914 m (3 ft). The experiment was performed with the upper pool and lower pool reduced by 0.914 m (3 ft). This is not a true representation of a raised floor since raising the floor requires that the ports also be raised. Raising the lock ports

decreases the distance from the lower pool or bottom of a moored barge to the port (submergence), which reduces the space available for energy dissipation of the water jets. This submergence depth is crucial to the performance of the filling and emptying system. Hawser forces were measured during filling operations with a 4-min valve speed, and these lowered pool els. The longitudinal hawsers were similar to those measured with the original design, Plate 35. The transverse hawsers were higher than those measured with the original design, but were not excessive. The results indicated that this design was probably feasible, so the model was modified to perform additional experiments with the floor raised.

Type 2 Culvert Design, Type 5 Chamber Design

The ports located in the floor culverts also had to be raised to accommodate the higher floor el. The lock floor was raised from el 165.202 to el 166.200, and the bottom of the ports were also placed at el 166.200. The port modification was designated the Type 2 culvert design and is shown in Plate 36. The bottom of the culverts in the ported section was also raised from el 162.457 to el 162.620. This required transitions in the culverts both upstream and downstream from the ported sections of the floor culverts. These elevation transitions were accomplished over a 15.240-m- (50-ft-) length section of the culverts upstream and downstream from the ported culverts. The raised lock floor modification with the raised ports was designated the Type 5 chamber design.

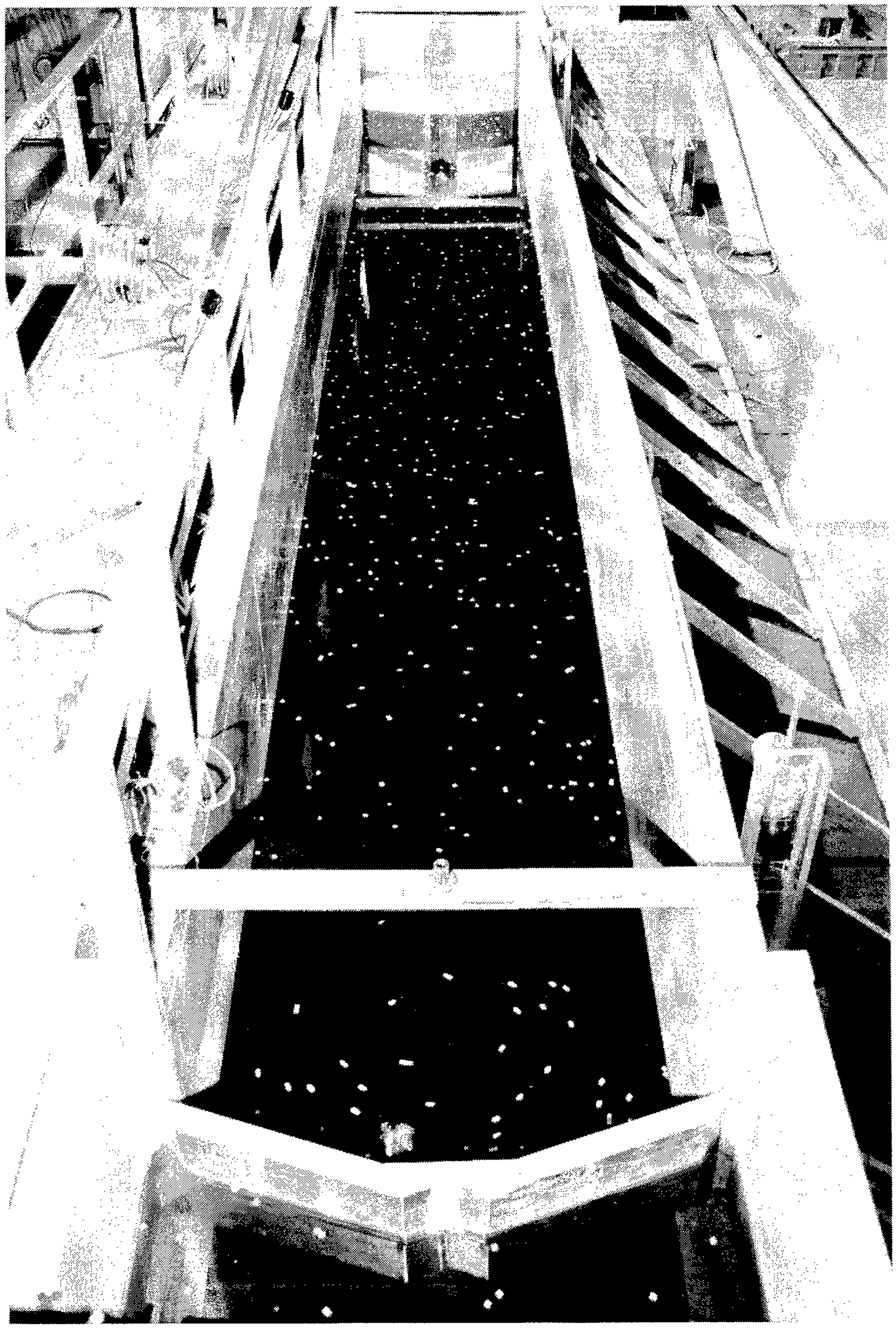
Hawser forces were measured during filling with the Type 2 culverts and Type 5 chamber for 2-, 4-, and 8-min valve operations to evaluate the performance of these designs. The average of the maximum longitudinal downstream hawsers measured with the Type 2 culverts and Type 5 chamber for the 2-min valve operation was 82.74 kN (9.3 tons), compared with 88.07 kN (9.9 tons) with the original design. The average of the maximum longitudinal upstream hawsers for the 2-min valve operation was 61.39 kN (6.9 tons), compared with 80.07 kN (9.0 tons) with the original design. The results from the hawser experiments with the Type 2 culverts and Type 5 chamber design are shown in Plate 37. The hawsers were very similar to those measured with the Type 1 design except for the left transverse hawsers for the 4- and 8-min valve speeds. These were slightly higher than those measured with the original design, but were still considered acceptable with the 4- and 8-min valves.

The filling times determined with the Type 2 culverts and the Type 5 chamber for the 2-, 4-, and 8-min valve operations were 7.6, 8.7, and 10.7 min, respectively. The filling times with the 4- and 8-min valves were slightly slower than those determined with the Type 1 design. There is more head loss in the Type 2 culverts and the Type 5 chamber because of the culvert transitions. The velocities in the culvert with the slower

valves remain higher for longer periods, which results in the slightly slower fill times.

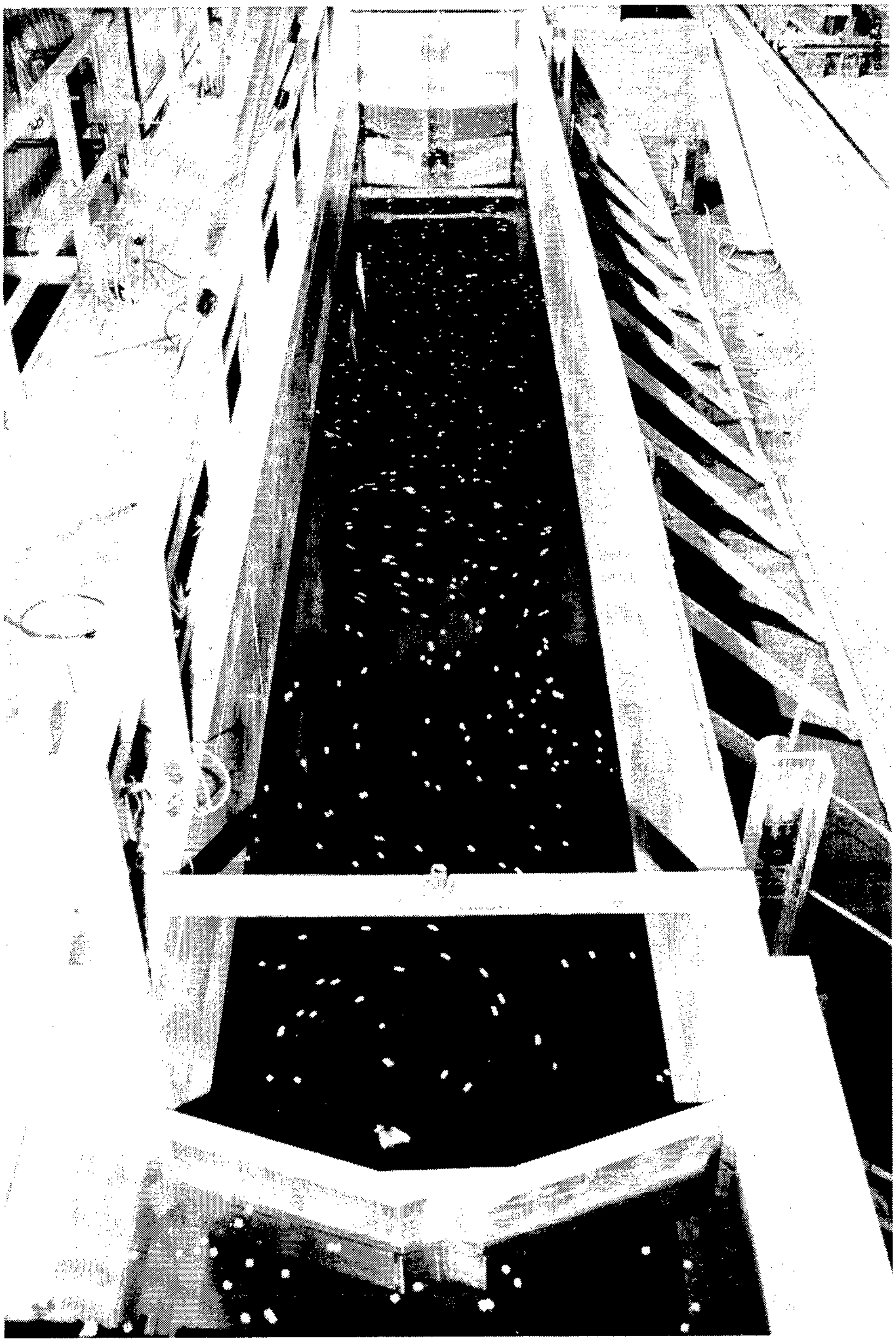
The emptying times determined with the Type 2 culverts and the Type 5 chamber for the 2-, 4-, and 8-min valve operations were 7.7, 8.3, and 10.5 min, respectively. The emptying time with the 2-min valve was slightly slower than those determined with the Type 1 design and was similar with the 4- and 8-min valves.

The hawser forces measured during emptying with 2-, 4-, and 8-min valves are shown in Plate 38. The longitudinal downstream hawsers were slightly higher than those measured with the Type 1 design, and the upstream hawsers were slightly lower. The transverse hawsers were similar to those measured with the Type 1 design. The hawser forces were considered acceptable during emptying operations with the Type 2 design culvert and the Type 5 chamber design. The flow conditions during filling operations with the Type 2 culverts are shown in Figure 8.



a. As filling started

Figure 8. Surface currents in lock chamber during filling operations with Type 2 culvert and Type 5 chamber (recommended) design, 4-min valve time, time exposure 15 sec (Sheet 1 of 5)



b. Two minutes after filling started

Figure 8. (Sheet 2 of 5)

c. Four minutes after filling started

Figure 8. (Sheet 3 of 5)

d. Six minutes after filling started

Figure 8. (Sheet 4 of 5)

e. Eight minutes after filling started

Figure 8. (Sheet 5 of 5)

4 Summary and Conclusions

A Type 4 vortex formed in the in the upper approach with the 7.315-m (24-ft) lift and 2-min valve operation. Minor modifications to the upper approach were made to reduce the strength of the vortices. The flow conditions in the upper approach were improved with the Type 3 approach topography shown in Plate 16. The flow was distributed more uniformly depthwise, which helped reduce the strength of the vortices.

Model experiments with the Type 1 design (original design) filling and emptying system revealed the performance was acceptable for the 4-min valve operation, which the system was designed for, with the upper pool el of 179.832 (590 ft) and lower pool el of 172.517 (566 ft). The maximum longitudinal hawser forces with the Type 1 design filling and emptying system were above the desired limit of 44.48 kN (5 tons) for this lift with the 2-min valve operation. Minor modifications to the baffling arrangement and the port extensions inside the lock chamber were made in an attempt to reduce longitudinal hawsers during filling operations with the 2-min valve operation. No significant reductions were observed; since the performance was satisfactory with the 4-min valve, the Type 1 design filling and emptying was considered acceptable. No changes were made to the discharge outlet design.

Experiments were performed to evaluate raising the floor of the lock to reduce excavation and help save construction costs. The ports inside the floor culverts were raised to accommodate the higher floor el. The performance of this design, designated the Type 2 culverts and Type 5 chamber, was also acceptable. The hawser forces were similar to those measured with the Type 1 design, and the changes in the filling and emptying times were only slightly different from the Type 1 design. The performance of the lock with the Type 3 approach topography, the Type 2 culverts, the Type 5 chamber, and the Type 1 outlet was acceptable for the 7.315-m (24-ft) lift with valve operations of 4 min and slower. The lock filling time with these conditions determined from the model experiements was 8.7 min, and the lock emptying time was 8.3 min.

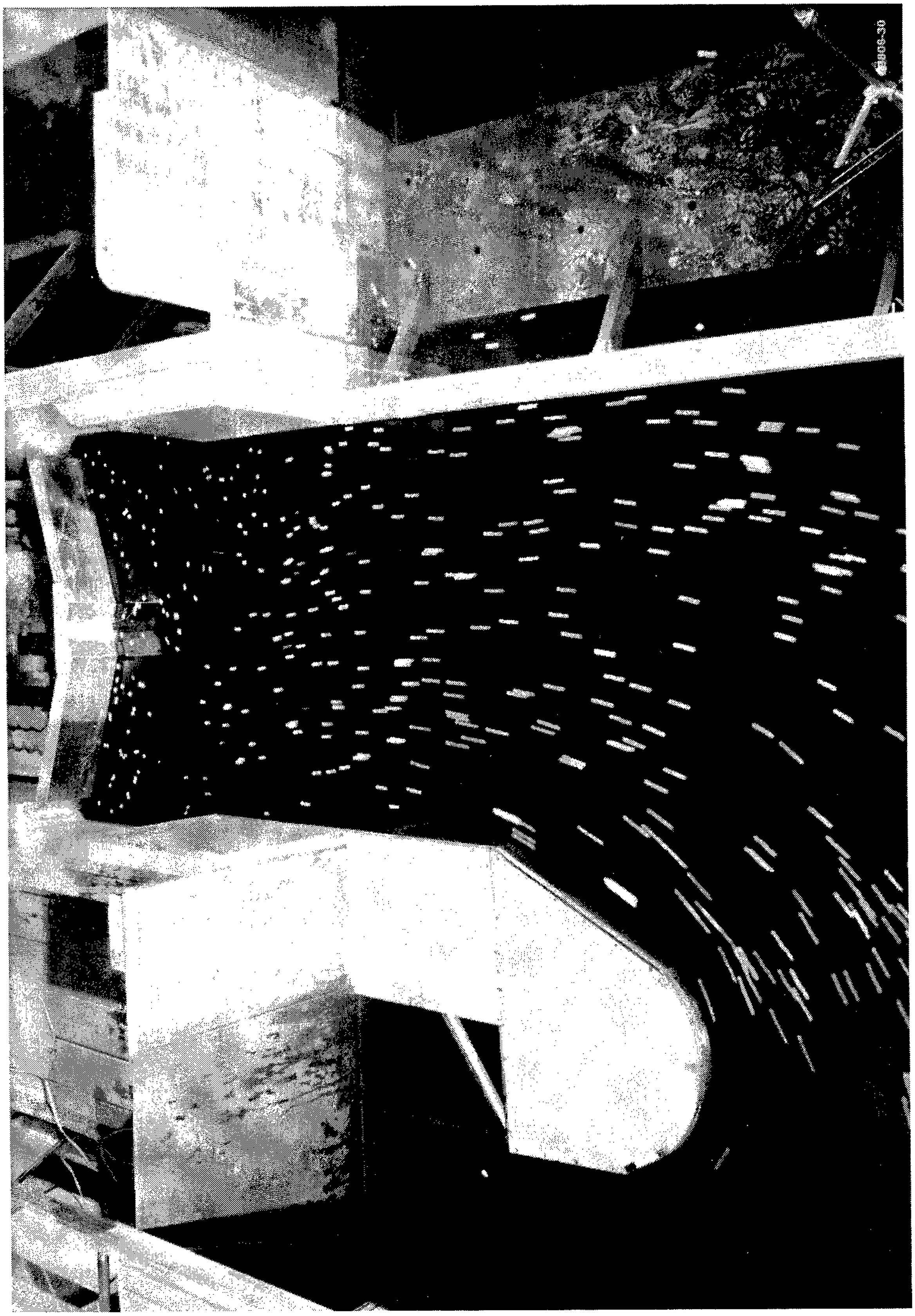
Vortices should be expected in the upper approach when the intakes are placed through the upper miter sill. The design approach is to minimize the strength of these vortices with minor modifications to the approach

topography. The flow conditions in the upper approach were acceptable with the 7.315-m (24-ft) lift, the 4-min valve operation, and Type 3 approach design; however, small vortices should be expected during the filling operations. The flow conditions in the upper approach with this design and valve speed are shown in Figure 9. If valve speeds faster than 4-min are allowed, stronger vortices should be expected.

The performance of the Marmet Lock was not evaluated for the entire range of pool conditions because of time and funding constraints. The 7.315-m (24-ft) lift was considered to be the critical condition for design, and the performance was assumed to be acceptable for lower lifts. These model experiments have shown that the in-chamber longitudinal culvert system developed for the larger McAlpine Lock with the 11.278-m (37-ft) lift performed well with the Marmet Lock. The curves in the culvert required to position the filling and emptying valves in the lock walls did not cause any undesirable (low pressures) flow conditions in the system.

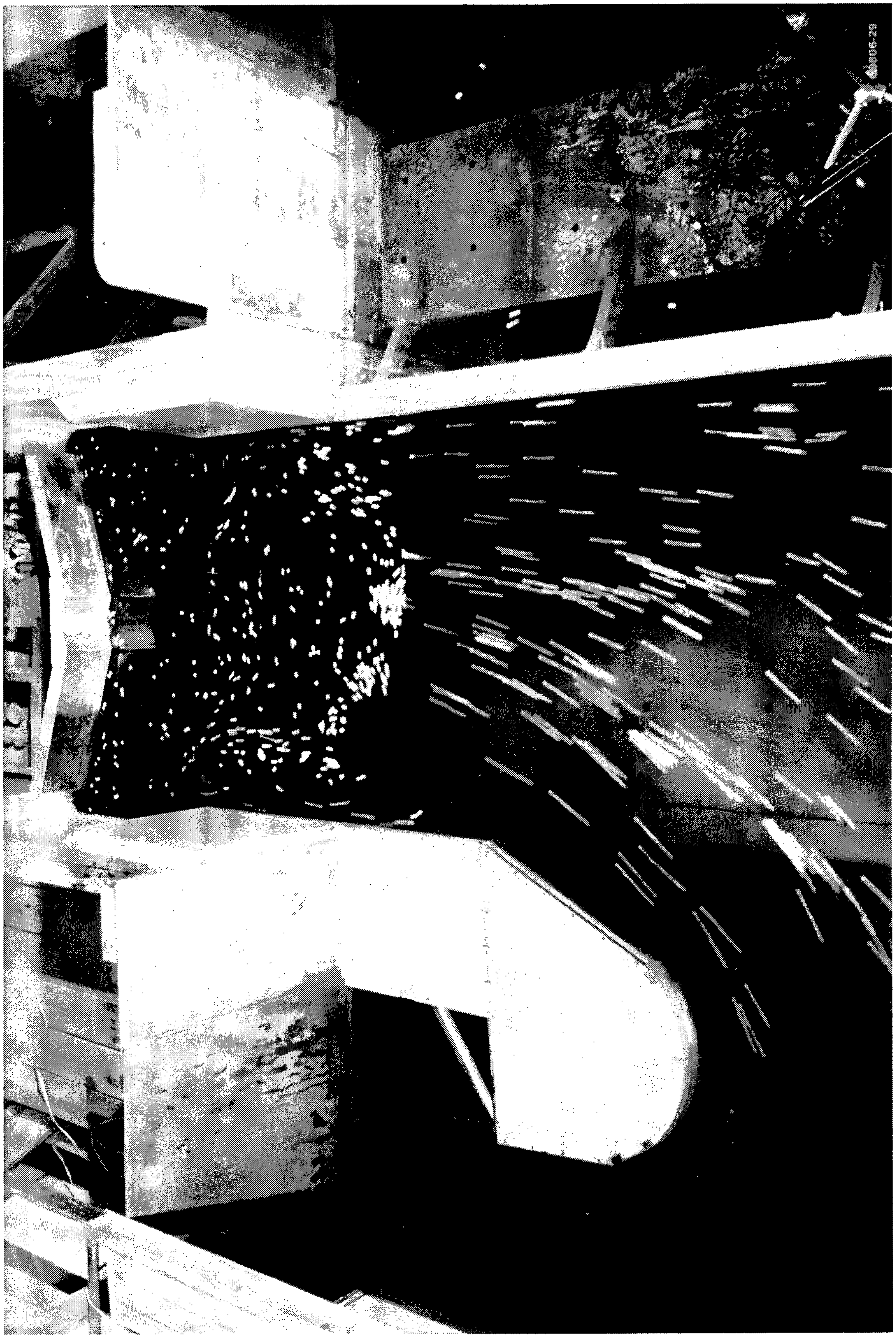
a. As filling started

Figure 9. Surface currents in upper lock approach during filling operations with Type 3 approach design and 4-min valve time, time exposure 15 sec (Sheet 1 of 5)



b. Two minutes after filling started

Figure 9. (Sheet 2 of 5)

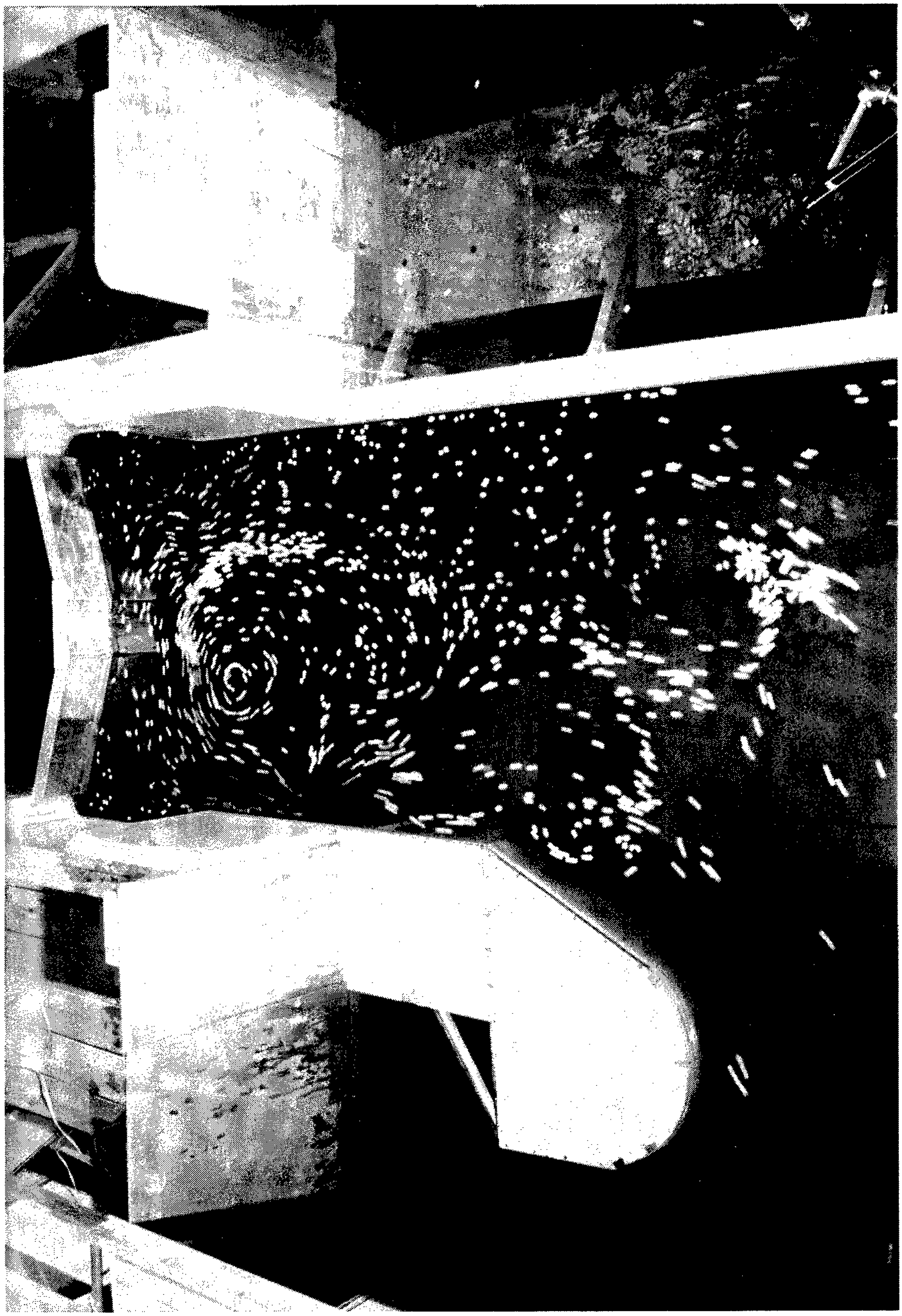


c. Four minutes after filling started

Figure 9. (Sheet 3 of 5)

d. Six minutes after filling started

Figure 9. (Sheet 4 of 5)



e. Eight minutes after filling started

Figure 9. (Sheet 5 of 5)

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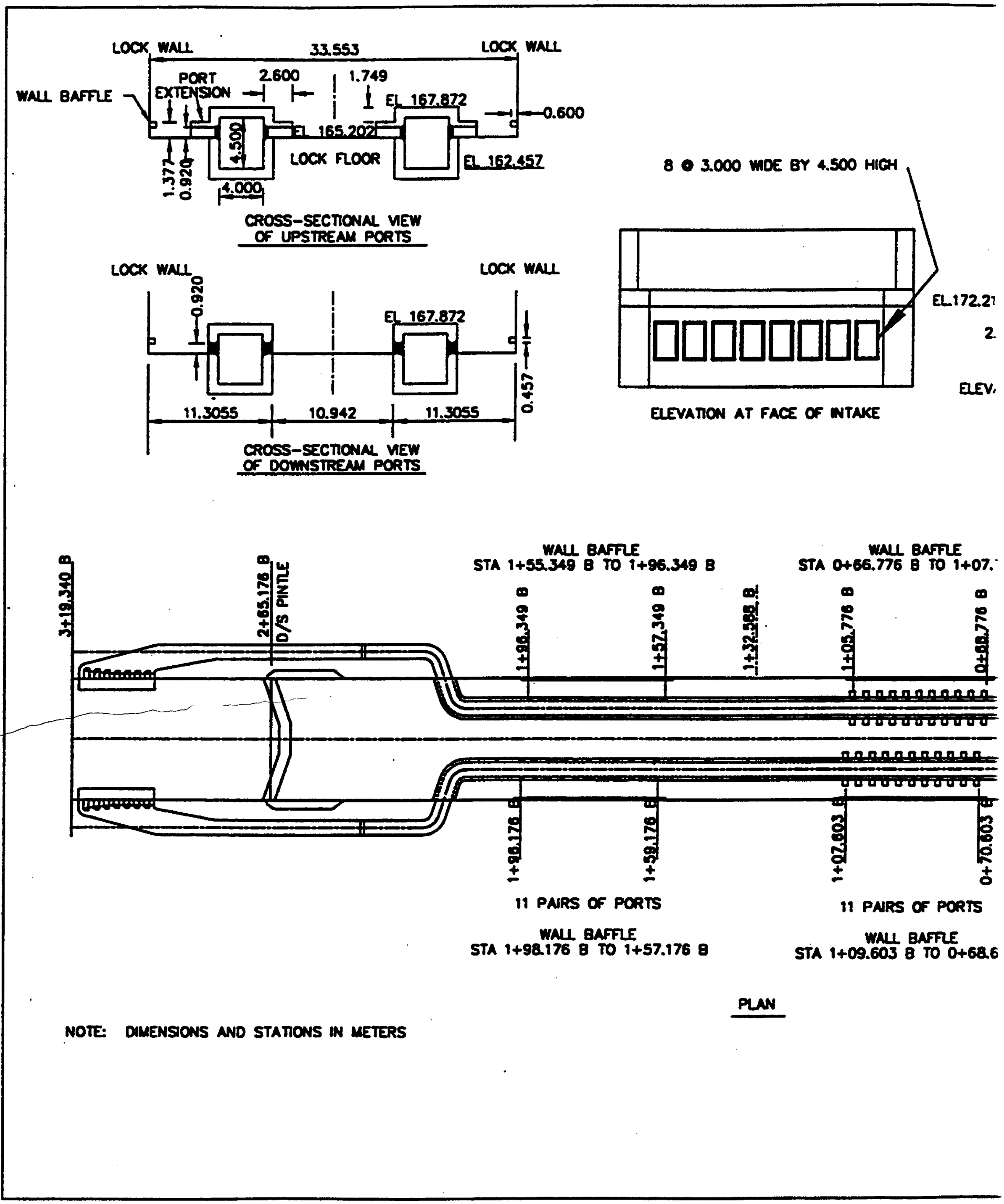
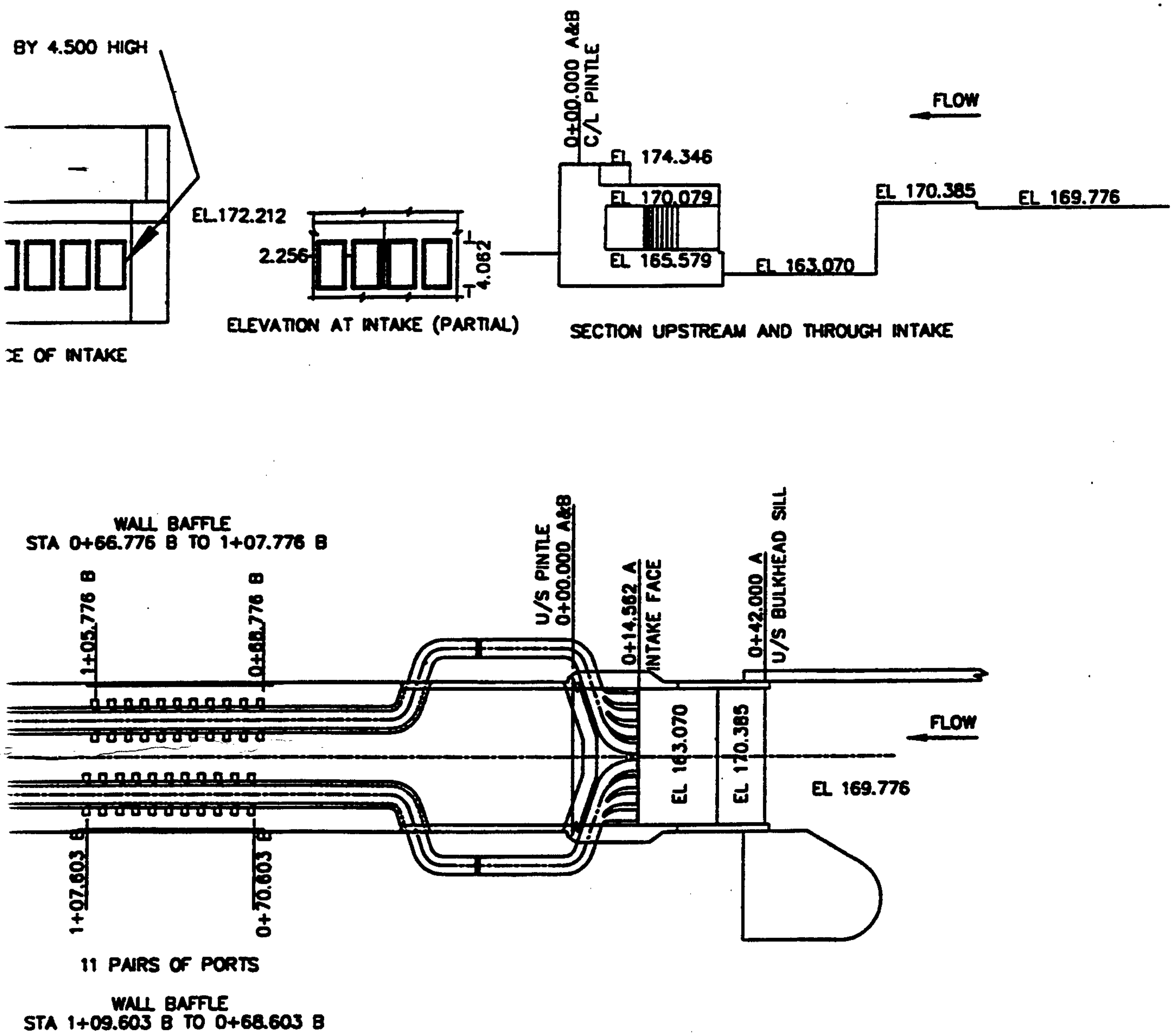
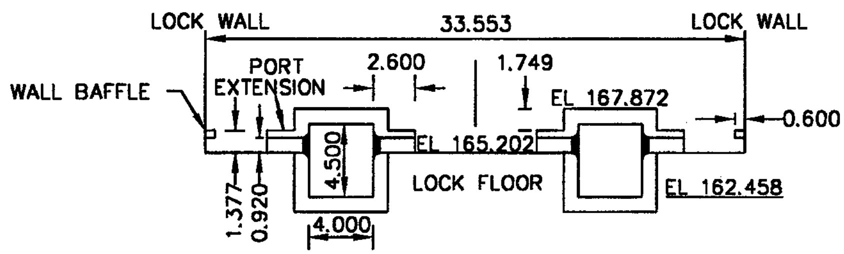

LOCK WALL
33.553
LOCK WALL
WALL BAFFLE
PORT EXTENSION
2.600
1.749
EL 167.872
0.600
EL 165.202
4.500
LOCK FLOOR
EL 162.457
1.377
0.920
4.000
CROSS-SECTIONAL VIEW OF UPSTREAM PORTS
8 @ 3.000 WIDE BY 4.500 HIGH
EL 172.21
ELEVATION AT FACE OF INTAKE
LOCK WALL
LOCK WALL
0.920
EL 167.872
0.457
11.3055
10.942
11.3055
CROSS-SECTIONAL VIEW OF DOWNSTREAM PORTS
WALL BAFFLE
STA 1+55.349 B TO 1+96.349 B
WALL BAFFLE
STA 0+66.776 B TO 1+07.
3+19.340 B
2+65.176 B
D/S PINTLE
1+96.349 B
1+57.349 B
1+32.588 B
1+05.776 B
0+68.776 B
1+98.176 B
1+59.176 B
1+07.603 B
0+70.603 B
11 PAIRS OF PORTS
11 PAIRS OF PORTS
WALL BAFFLE
STA 1+98.176 B TO 1+57.176 B
WALL BAFFLE
STA 1+09.603 B TO 0+68.6
PLAN
NOTE: DIMENSIONS AND STATIONS IN METERS

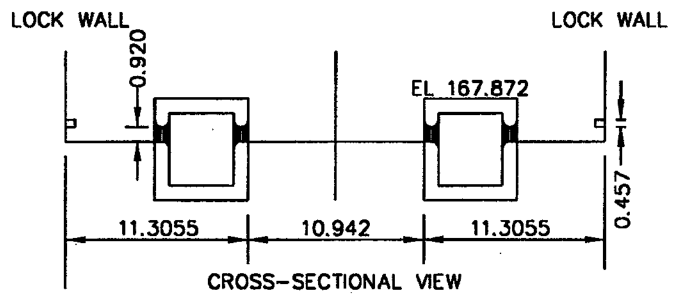


MARMET LOCK
TYPE 1 FILLING AND EMPTYING SYSTEM

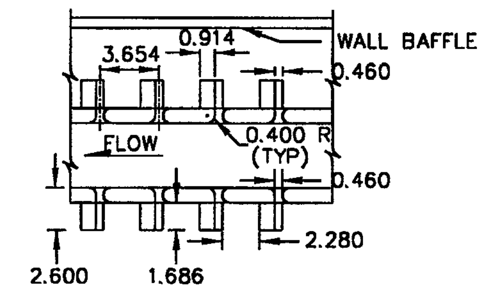
Plate 1



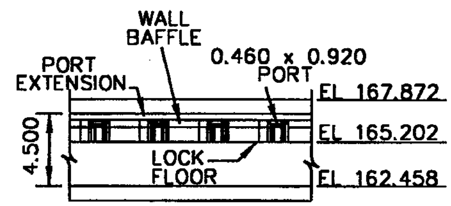
CROSS-SECTIONAL VIEW OF UPSTREAM PORTS



CROSS-SECTIONAL VIEW OF DOWNSTREAM PORTS



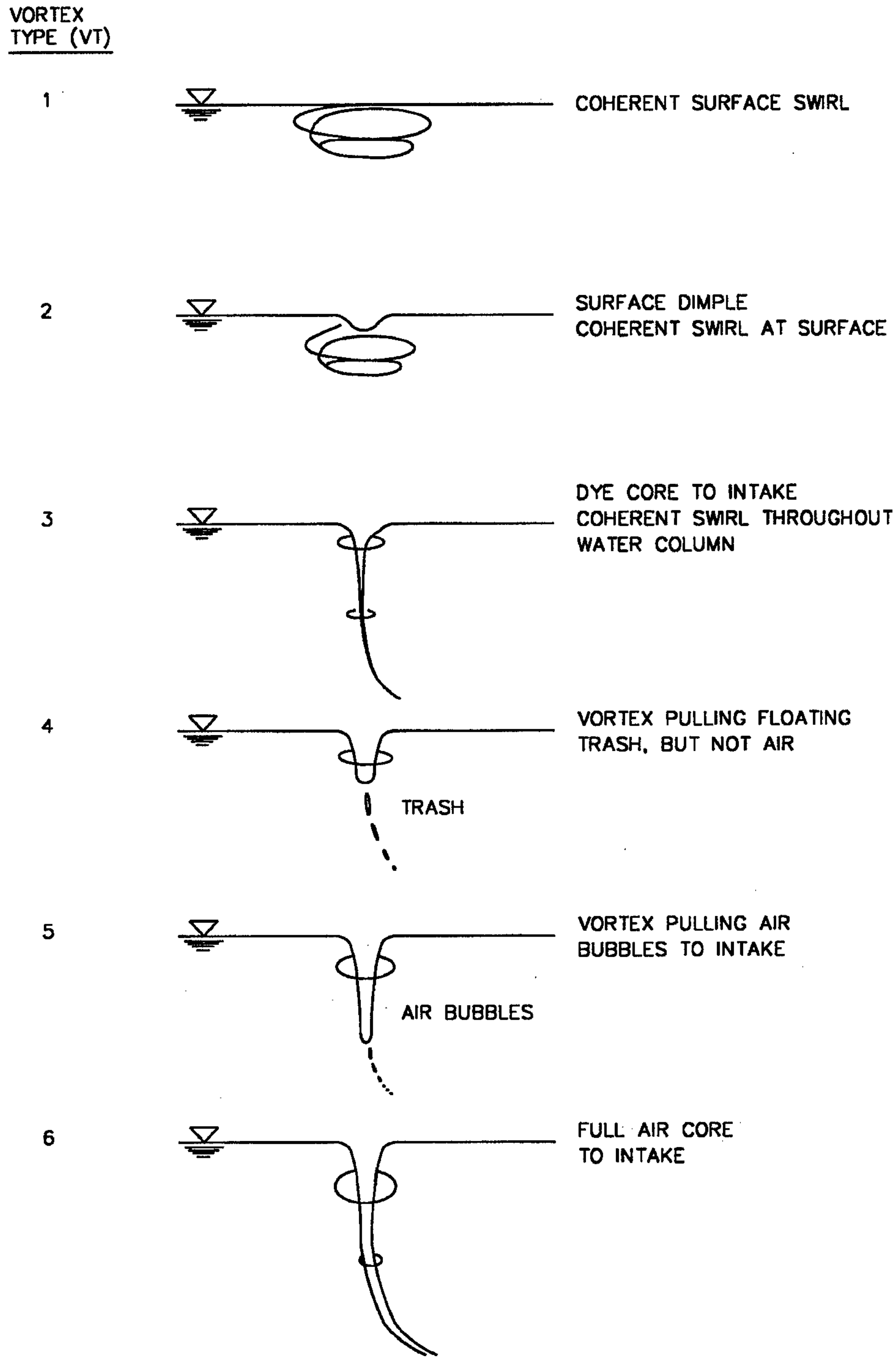
ENLARGED PLAN



SECTION OF ENLARGED PLAN

NOTE: DIMENSIONS AND ELEVATION IN METERS

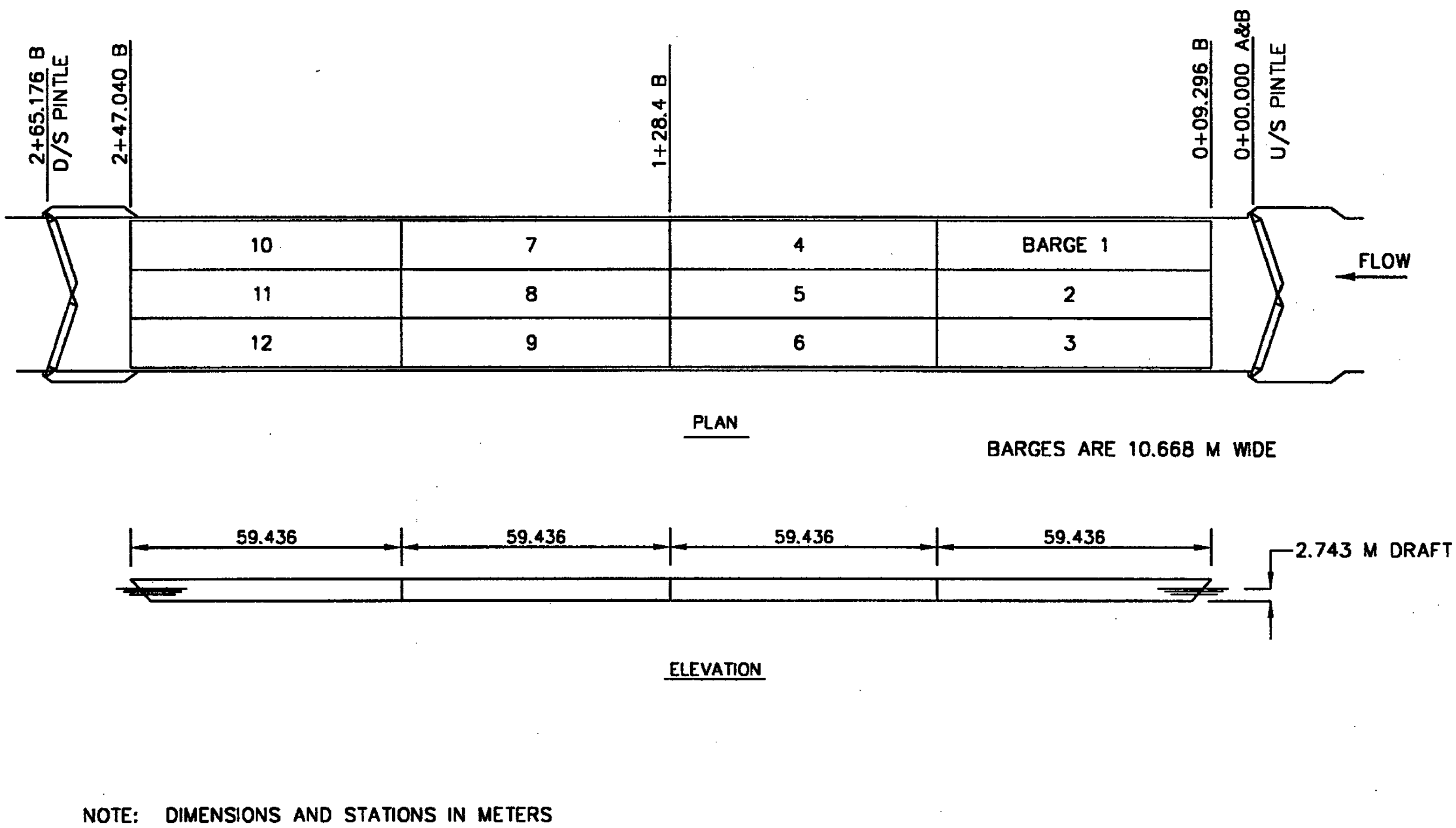
CULVERT AND PORT DETAILS
TYPE 1 DESIGN



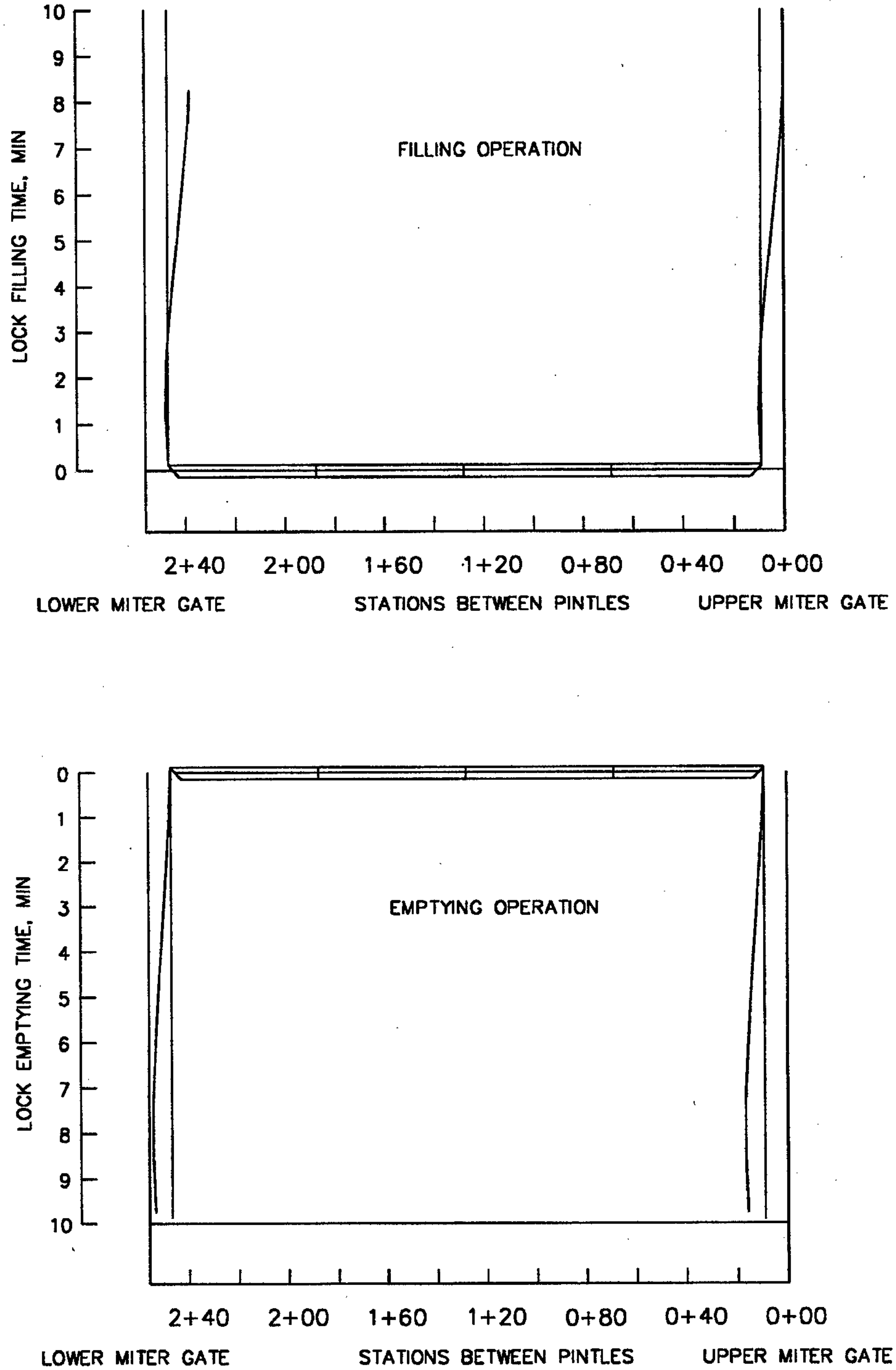
SOURCE: PADMANABHAN AND HECKER, 1984

ALDEN RESEARCH LAB
VORTEX TYPE CLASSIFICATION

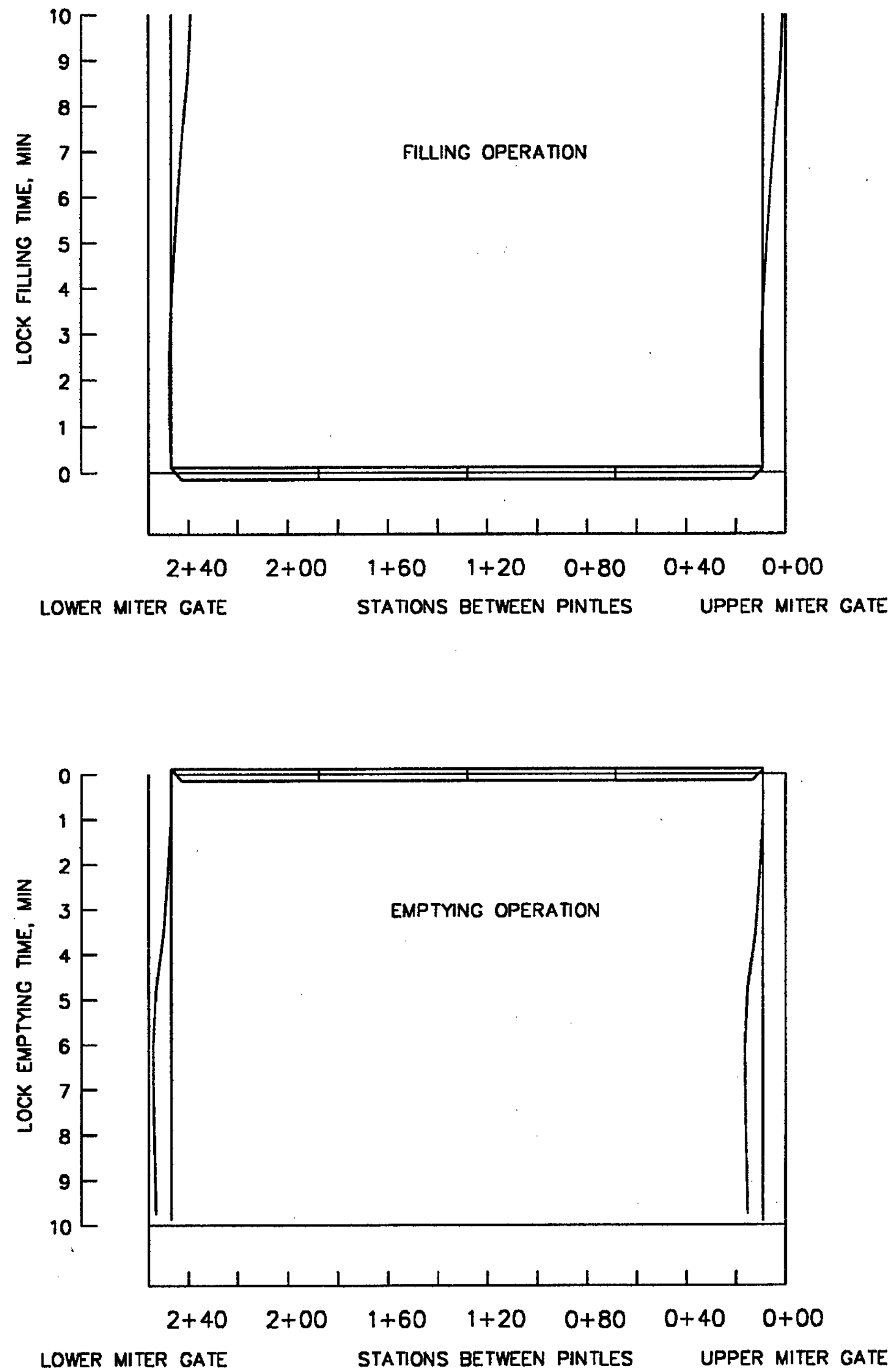
Plate 3



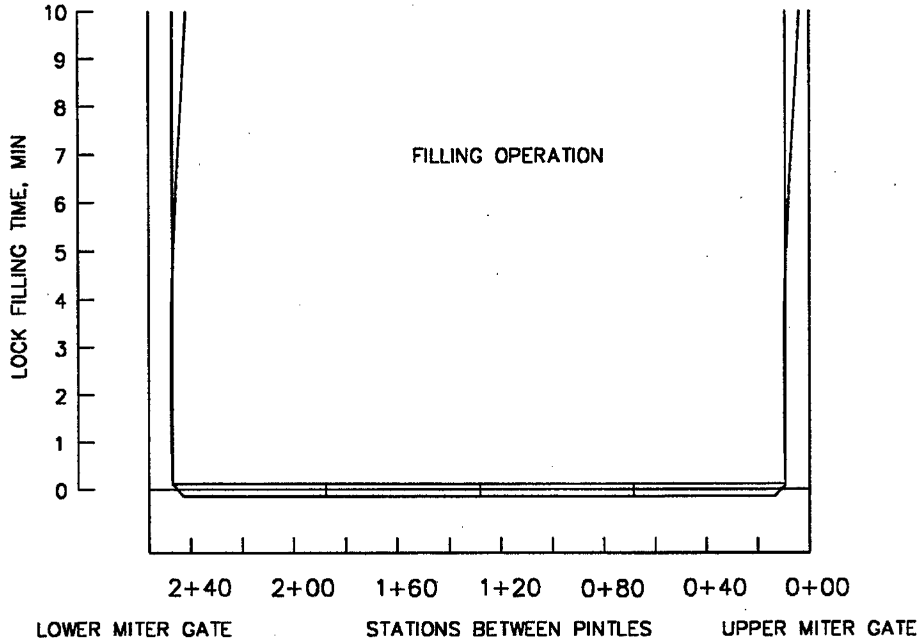
BARGE POSITION AND DETAILS

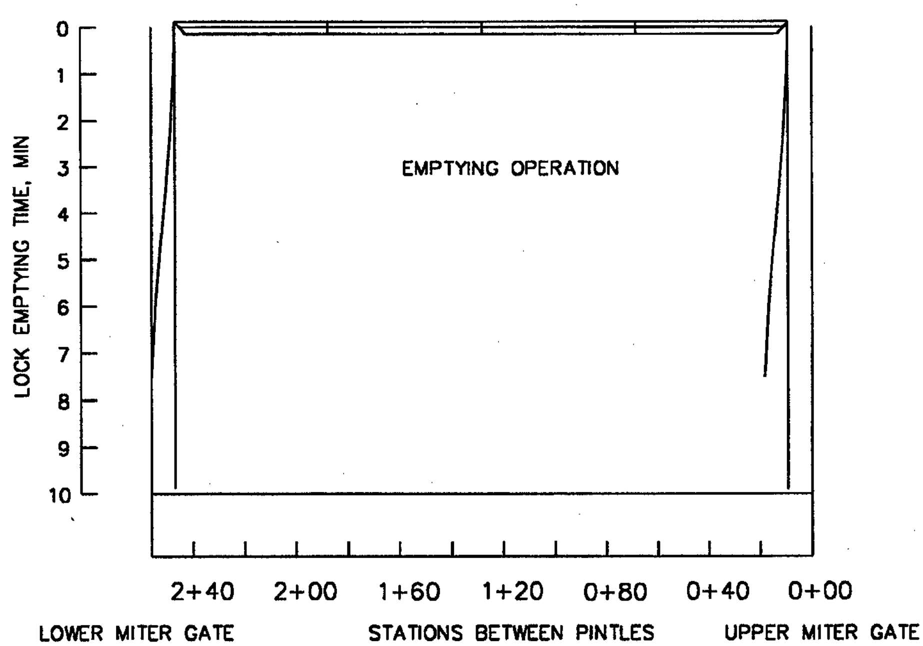


TYPICAL FREE TOW MOVEMENT
12-BARGE TOW
TYPE 1 (ORIGINAL) DESIGN
2-MIN VALVE OPERATION
U.P. EL 179.832, L.P. EL 172.517

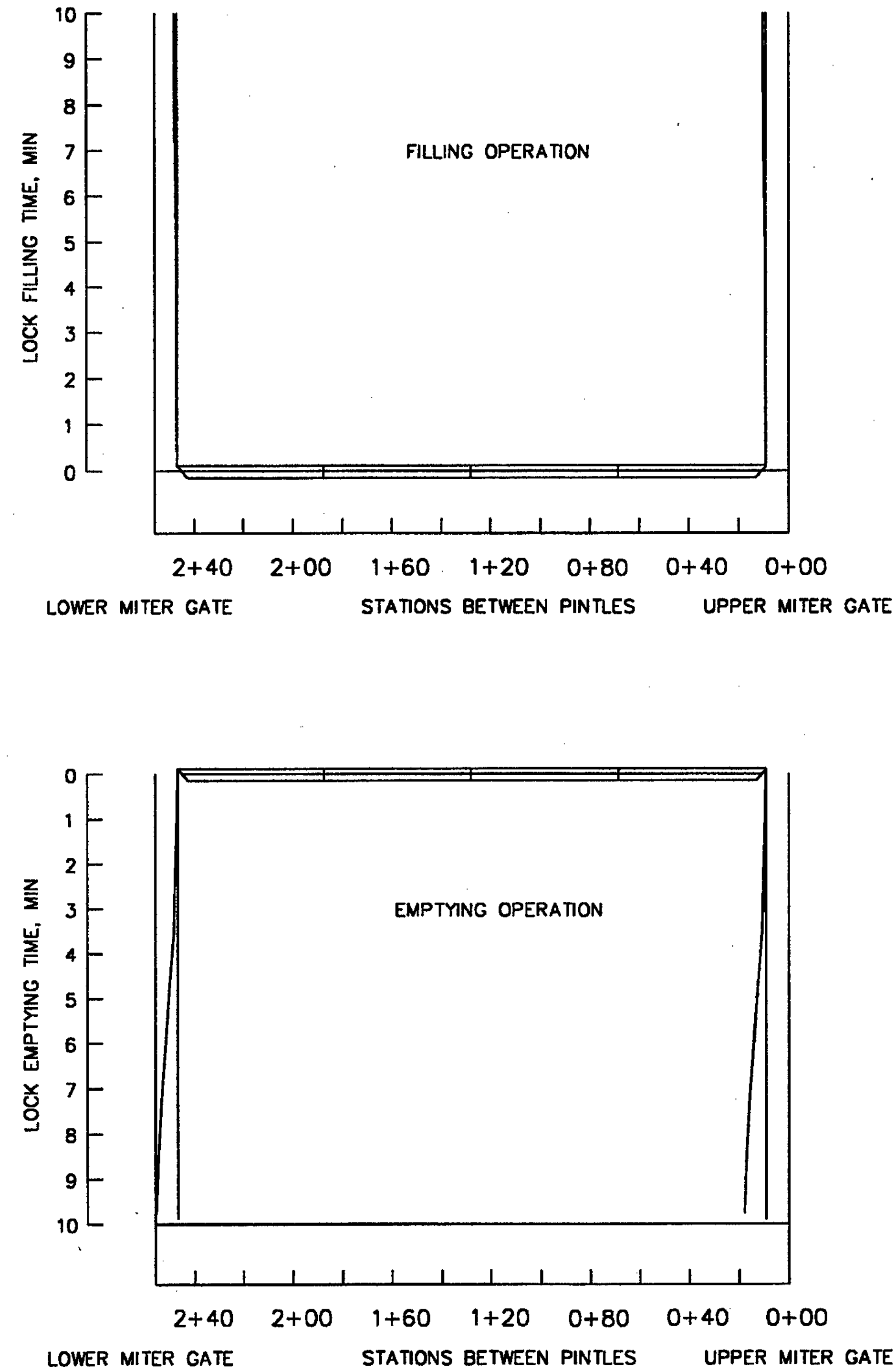


TYPICAL FREE TOW MOVEMENT
12-BARGE TOW
TYPE 1 (ORIGINAL) DESIGN
3-MIN VALVE OPERATION
U.P. EL 179.832,   L.P. EL 172.517

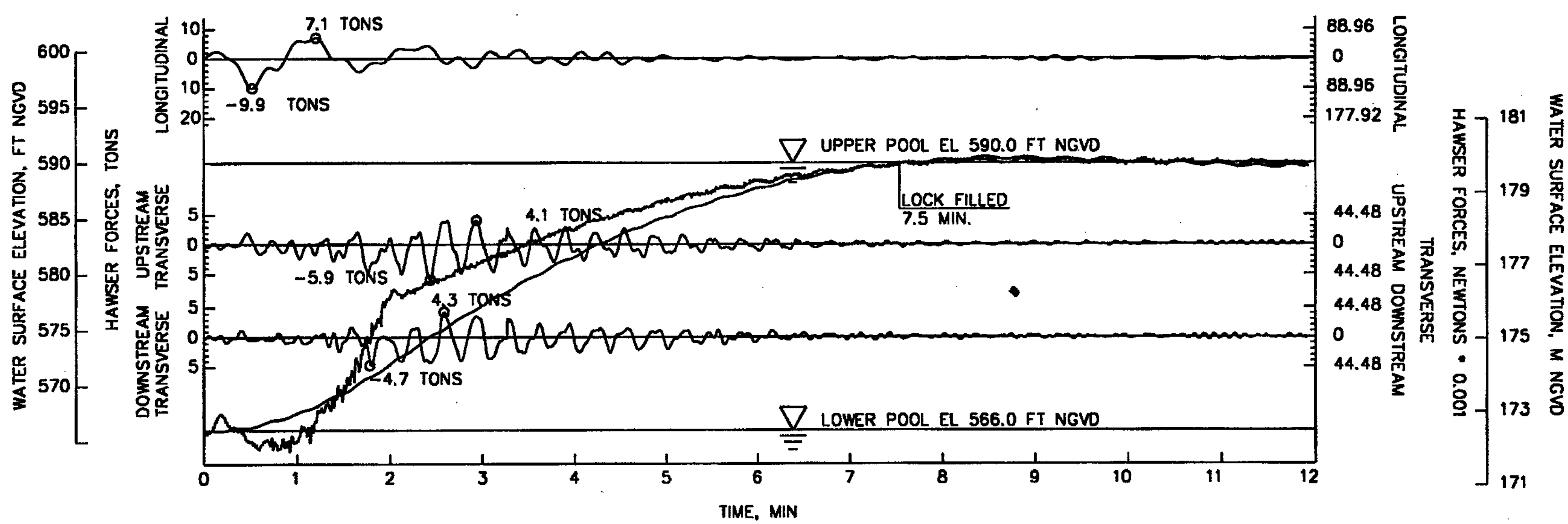




TYPICAL FREE TOW MOVEMENT
12-BARGE TOW
TYPE 1 (ORIGINAL) DESIGN
4-MIN VALVE OPERATION
U.P. EL 179.832, L.P. EL 172.517



TYPICAL FREE TOW MOVEMENT
12–BARGE TOW
TYPE 1 (ORIGINAL) DESIGN
8–MIN VALVE OPERATION
U.P. EL 179.832, L.P. EL 172.517

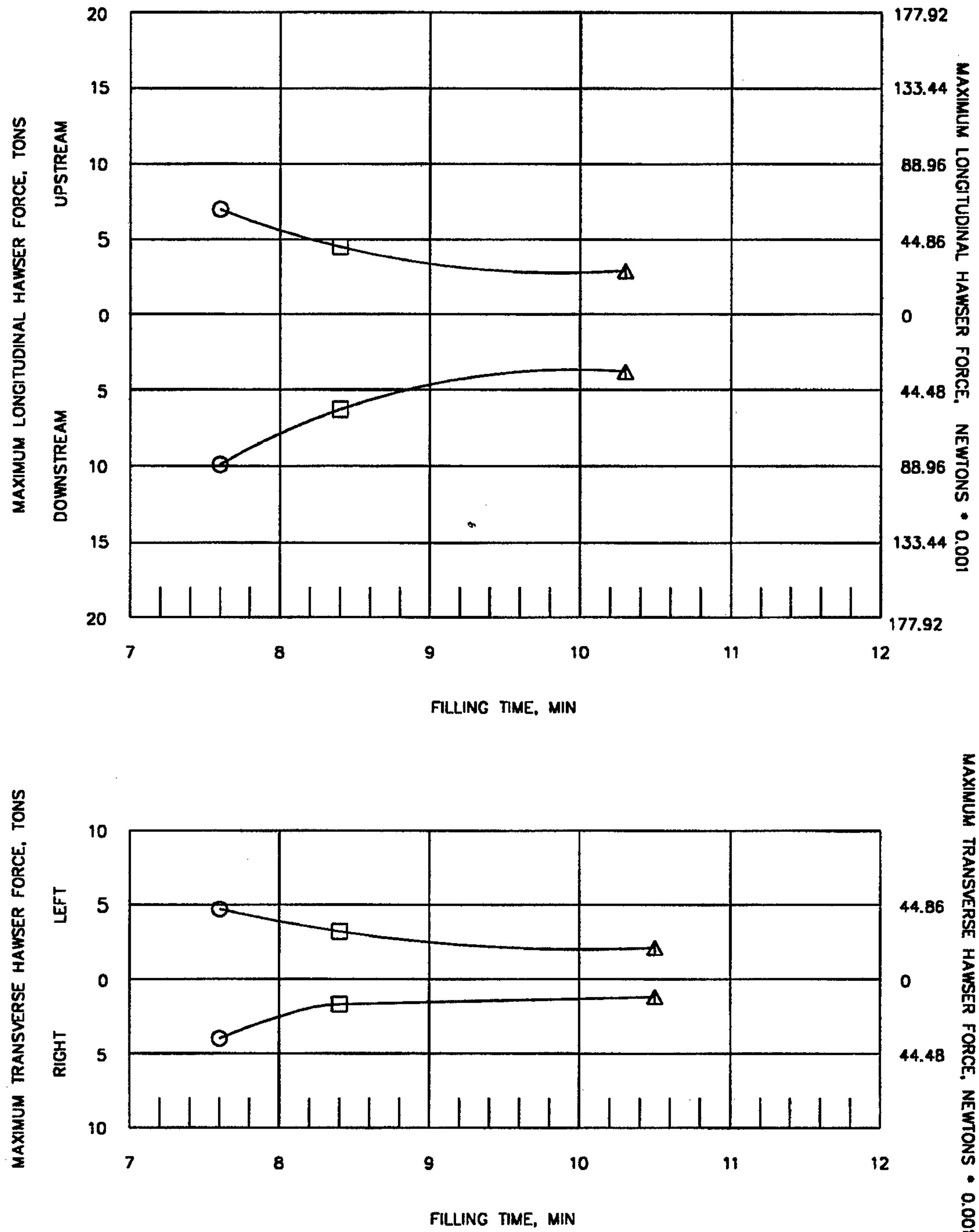


NOTE: NEGATIVE LONG. HAWSER INDICATES FORCE IN DOWNSTREAM DIRECTION

NEGATIVE TRANSVERSE HAWSER INDICATES FORCE TOWARDS LEFT SIDE OF CHAMBER

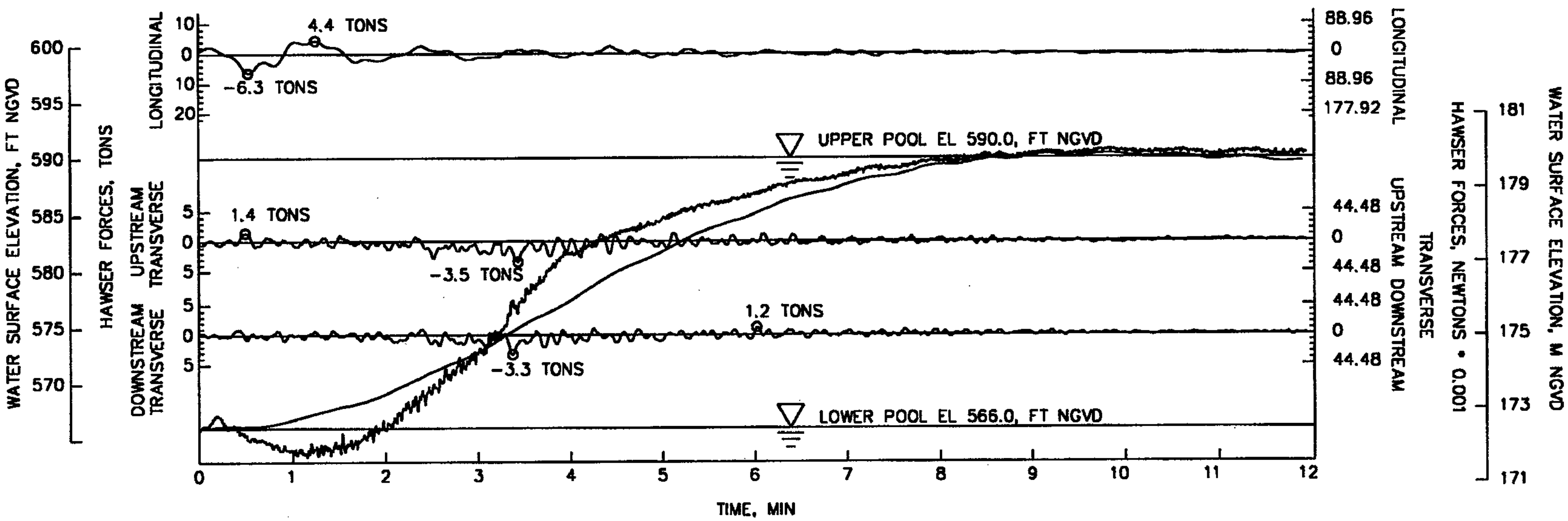
MARMET FILLING AND EMPTYING SYSTEM
TYPE 1 DESIGN
2-MIN NORMAL FILL – TEST 10

MAR2F.010



LEGEND	
SYMBOL	VALVE SCHEDULE, MIN
O	2
□	4
Δ	8

HAWSER FORCES
DURING FILLING
TYPE 1 DESIGN

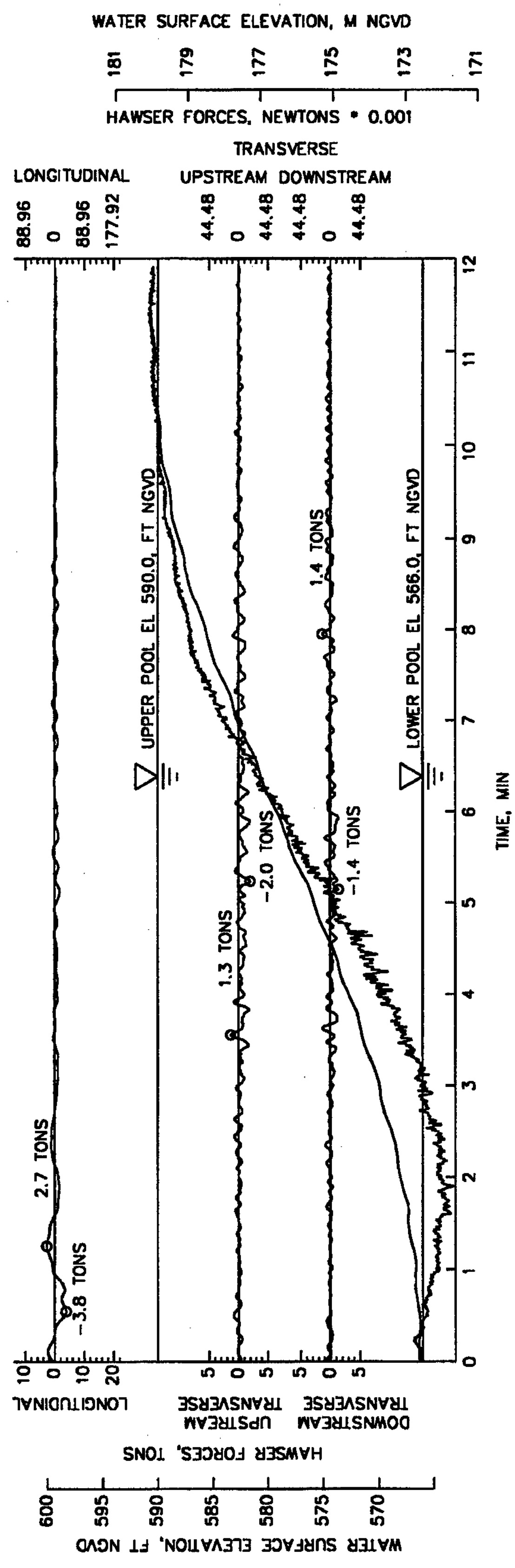


NOTE: NEGATIVE LONG. HAWSER INDICATES FORCE IN DOWNSTREAM DIRECTION

NEGATIVE TRANSVERSE HAWSER INDICATES FORCE TOWARDS LEFT SIDE OF CHAMBER

MARMET FILLING AND EMPTYING SYSTEM
TYPE 1 DESIGN
4-MIN NORMAL FILL - TEST 11

MAR4F.011

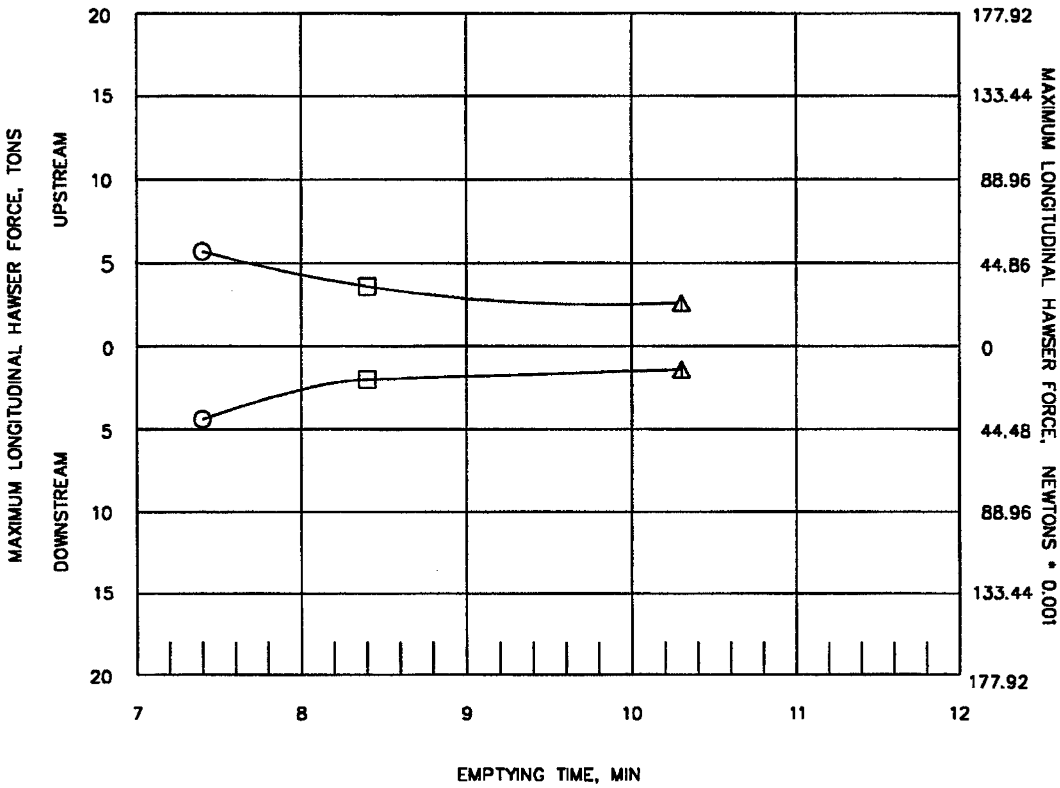


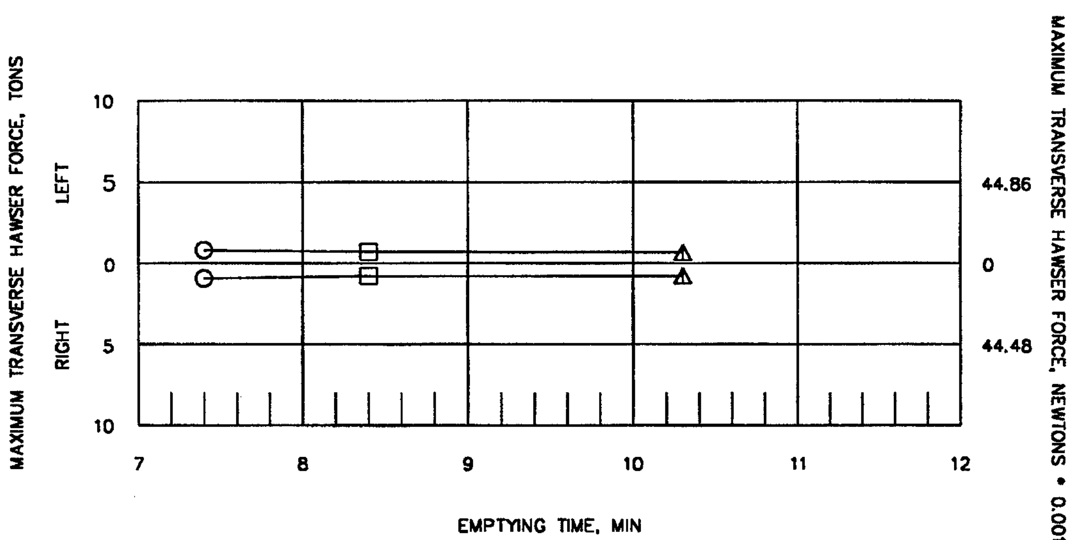
NOTE: NEGATIVE LONG. HAWSER INDICATES FORCE IN DOWNSTREAM DIRECTION

NEGATIVE TRANSVERSE HAWSER INDICATES FORCE TOWARDS LEFT SIDE OF CHAMBER

MARMET FILLING AND EMPTYING SYSTEM
TYPE 1 DESIGN
8-MIN NORMAL FILL - TEST 12

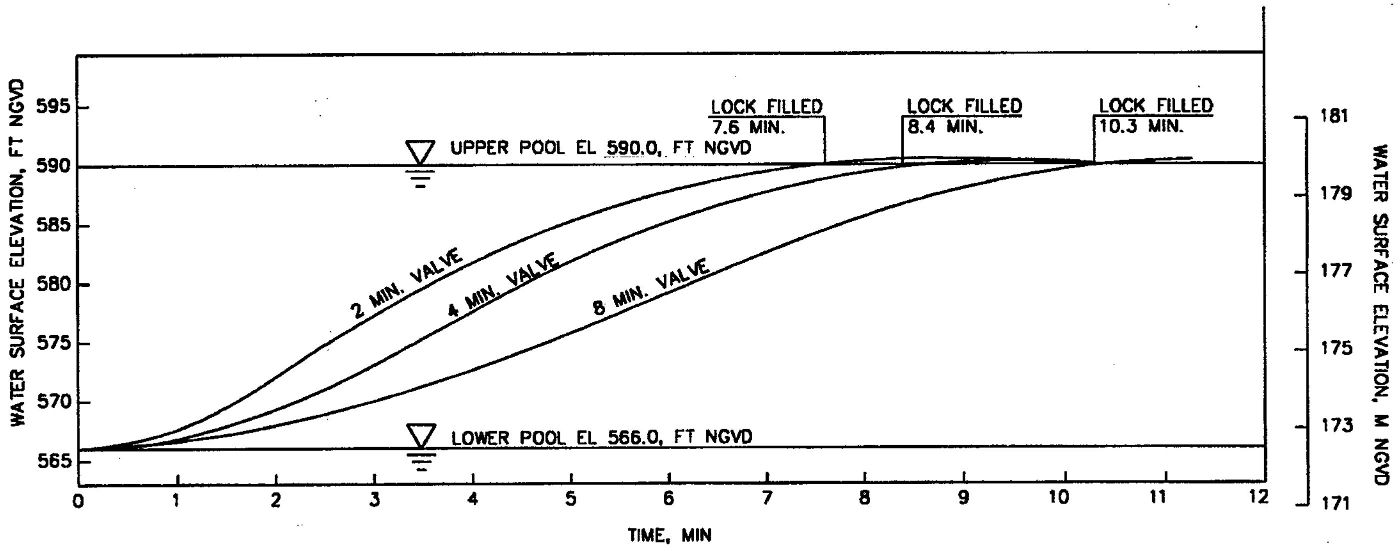
MARBF.012





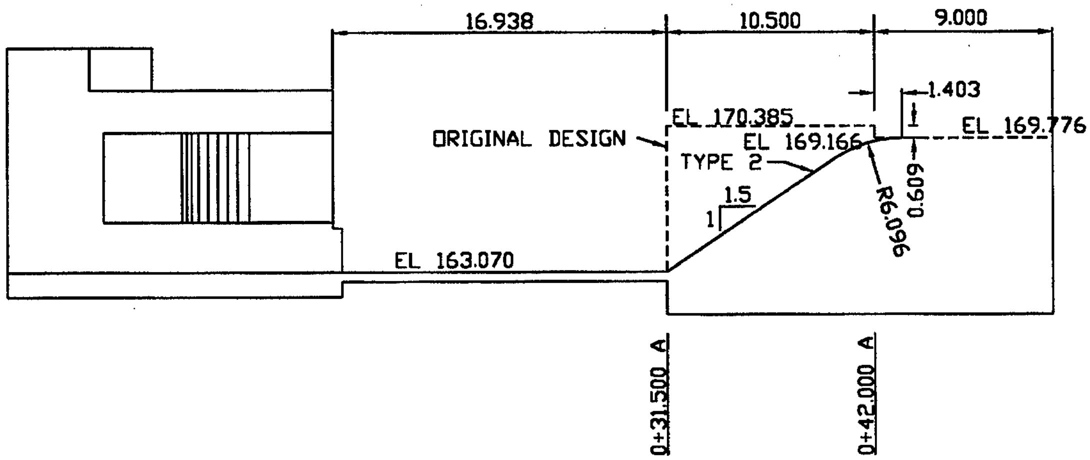
LEGEND	
SYMBOL	VALVE SCHEDULE, MIN
O	2
□	4
Δ	8

HAWSER FORCES
DURING EMPTYING
TYPE 1 DESIGN

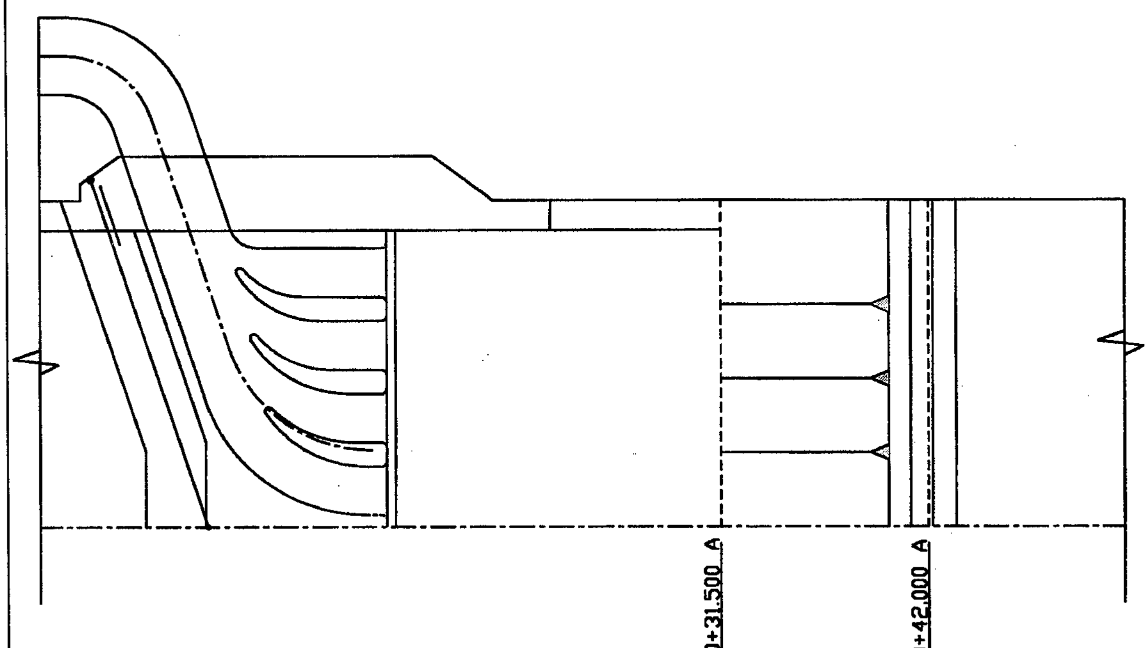


FILLING CURVES
TYPE 1 DESIGN
2, 4, AND 8 MIN. VALVES

248FILL



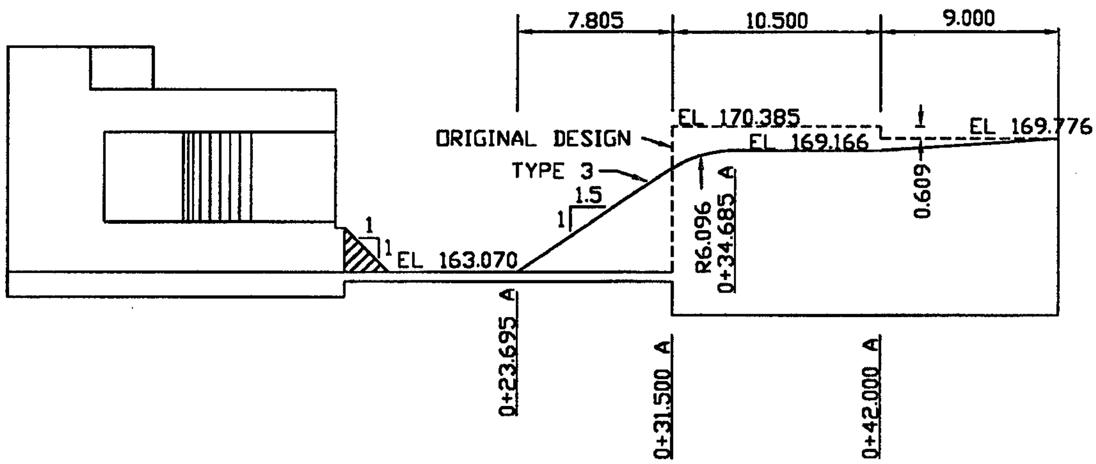
SECTION THOURGH UPPER APPROACH



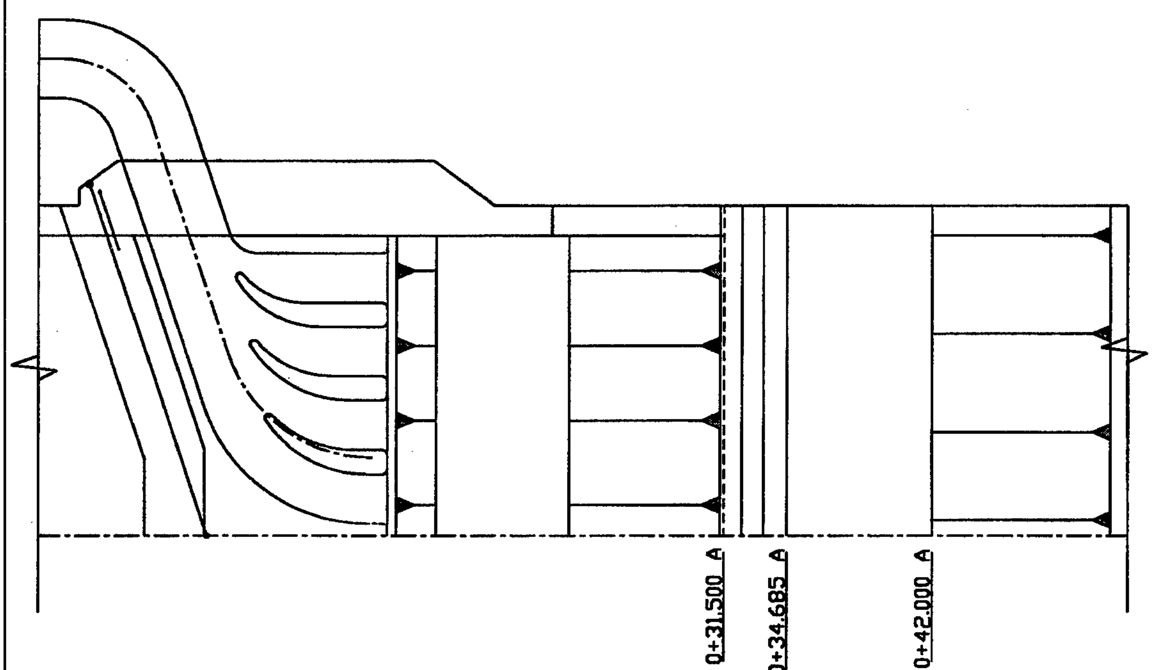
HALF PLAN OF UPPER APPROACH

DIMENSIONS AND EL'S IN METERS

APPROACH DESIGNS
ORIGINAL AND TYPE 2 DESIGNS



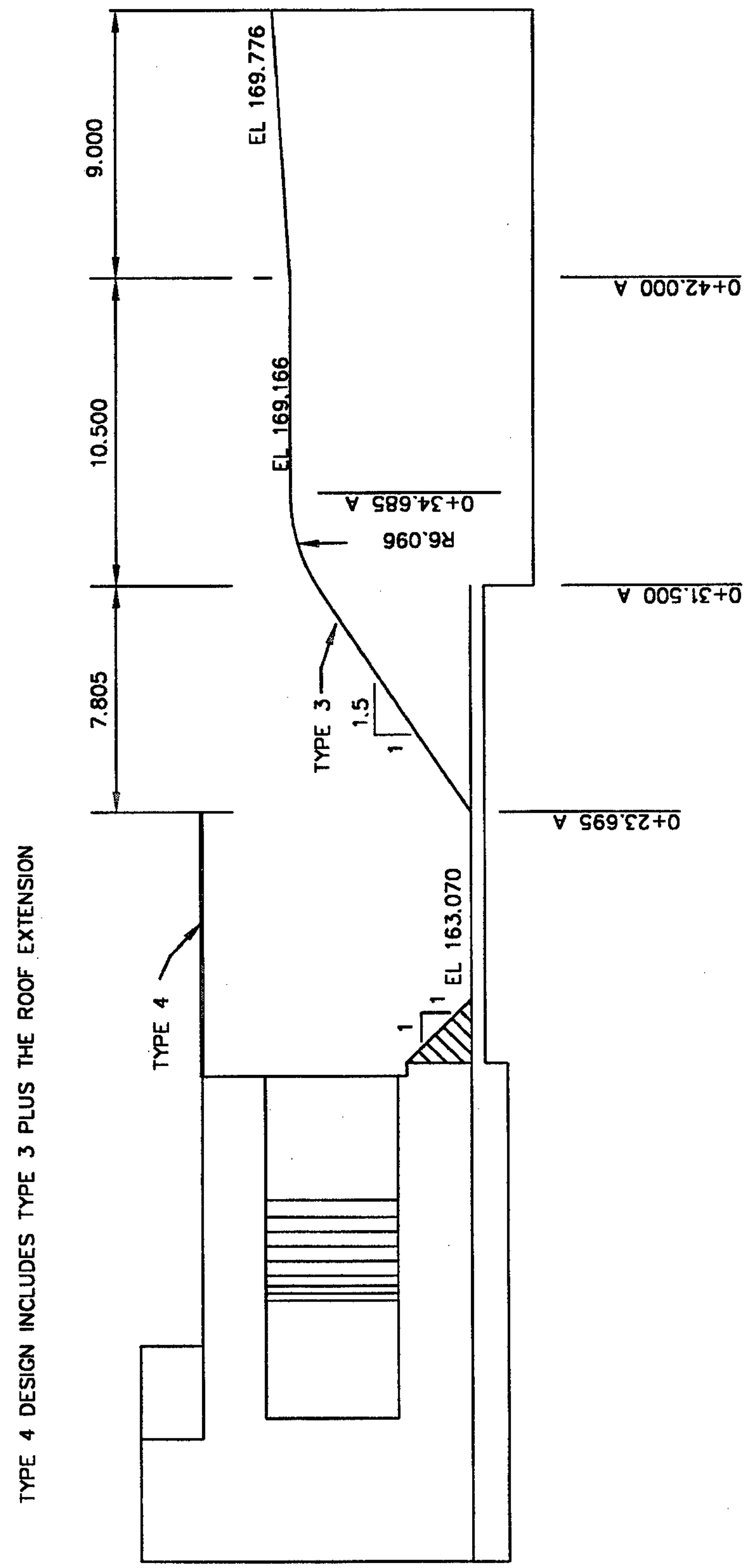
SECTION THOURGH UPPER APPROACH



HALF .PLAN OF UPPER APPROACH

DIMENSIONS AND EL'S IN METERS

APPROACH DESIGNS
ORIGINAL AND TYPE 3 DESIGNS



APPROACH DESIGNS
TYPES 3 AND 4 DESIGNS

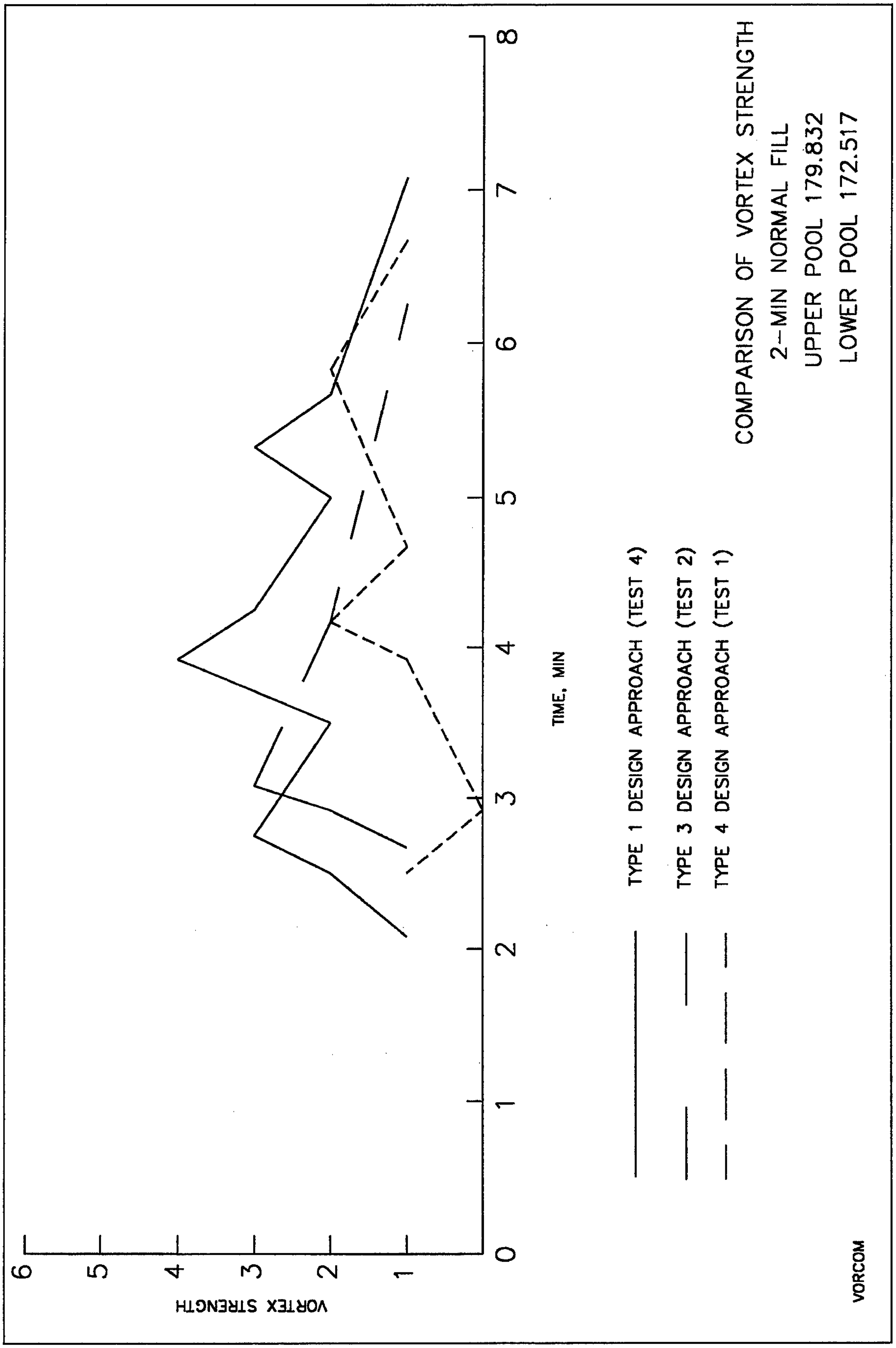
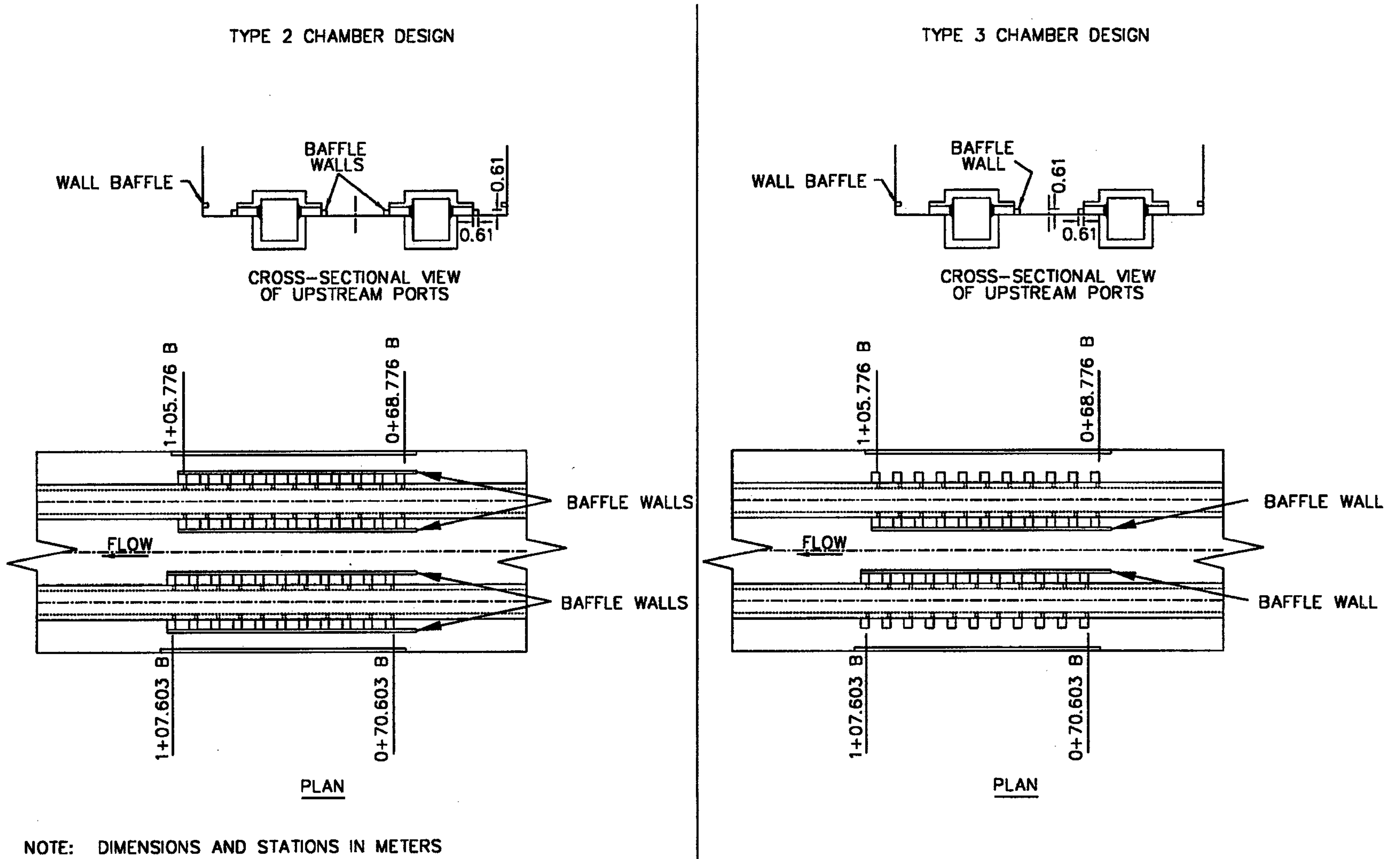
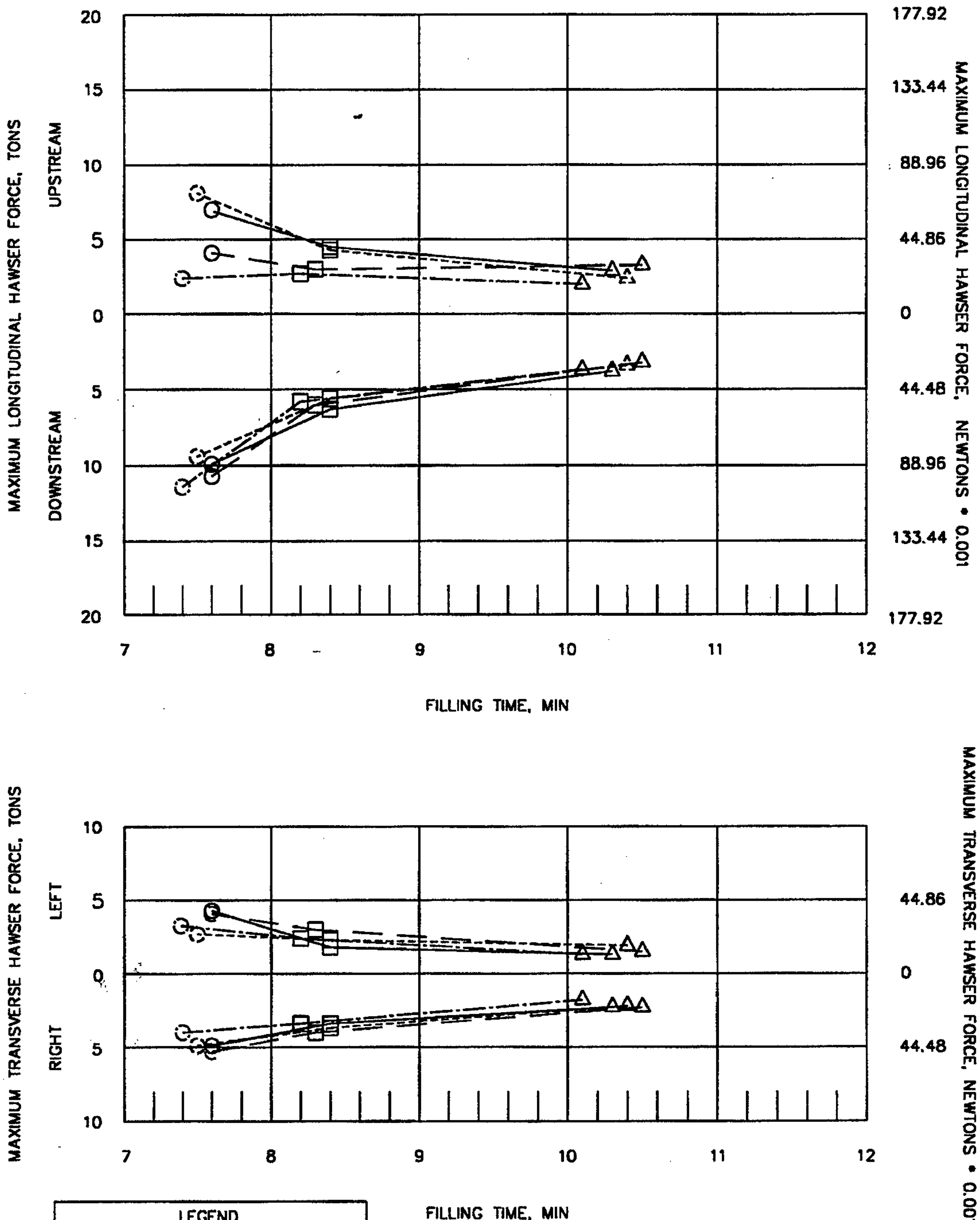

VORTEX STRENGTH
TIME, MIN
0
1
2
3
4
5
6
7
8
TYPE 1 DESIGN APPROACH (TEST 4)
TYPE 3 DESIGN APPROACH (TEST 2)
TYPE 4 DESIGN APPROACH (TEST 1)
COMPARISON OF VORTEX STRENGTH
2-MIN NORMAL FILL
UPPER POOL 179.832
LOWER POOL 172.517
VORCOM

Plate 18

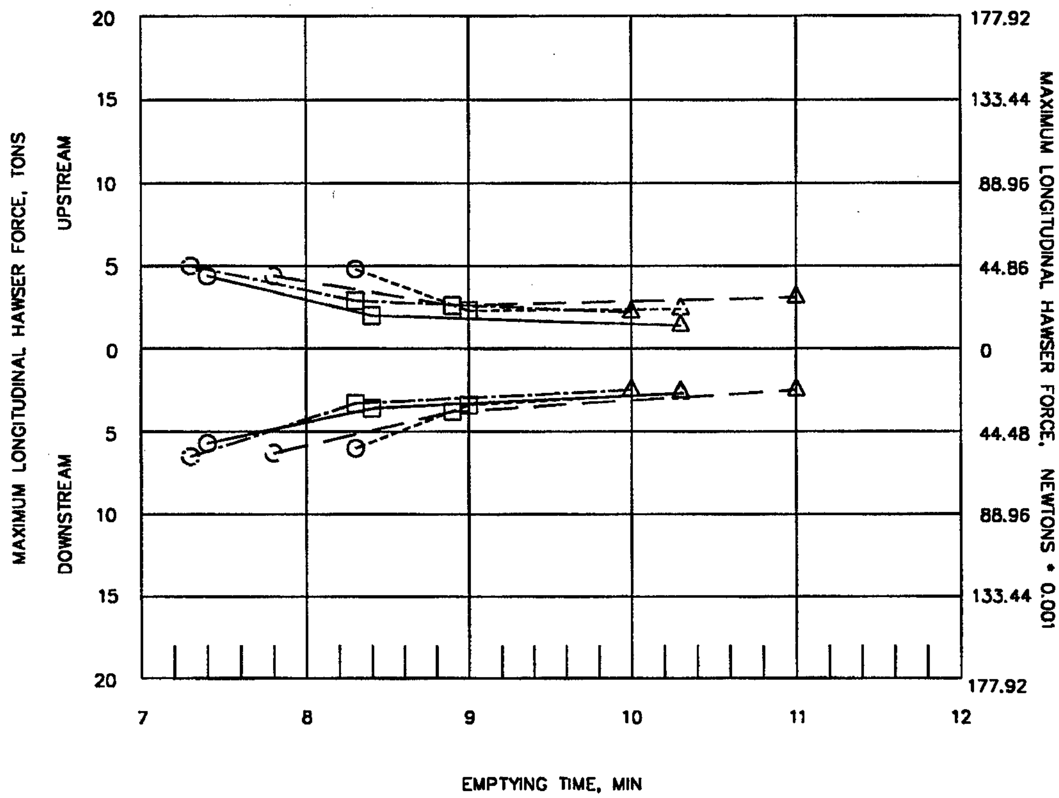


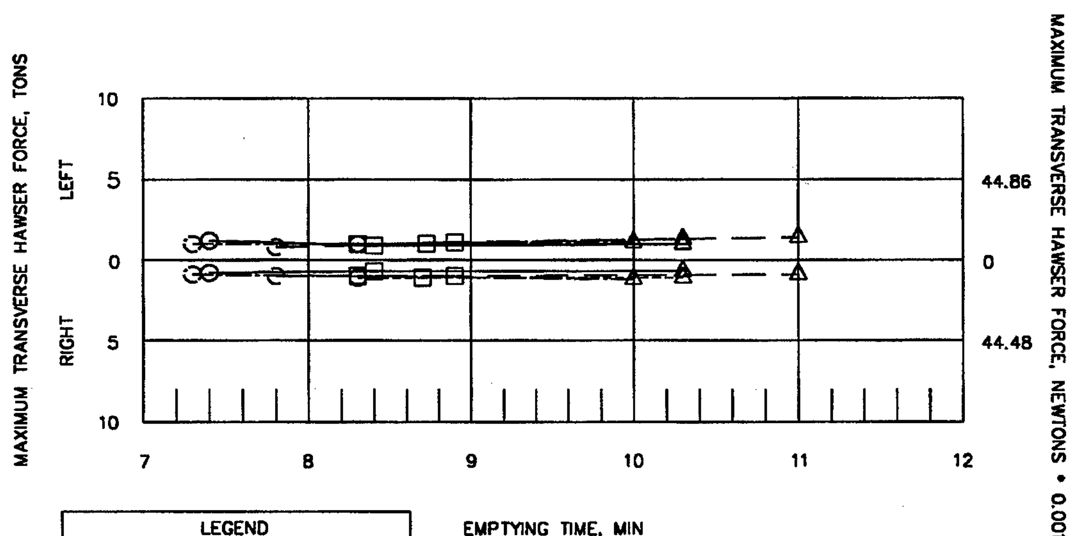
TYPES 2 AND 3 CHAMBER DESIGNS



LEGEND	
SYMBOL	VALVE SCHEDULE, MIN
○	2
□	4
△	8
LINE TYPE	DESIGN TYPE
———	1
—·—·—	2
— —	3
-------	4

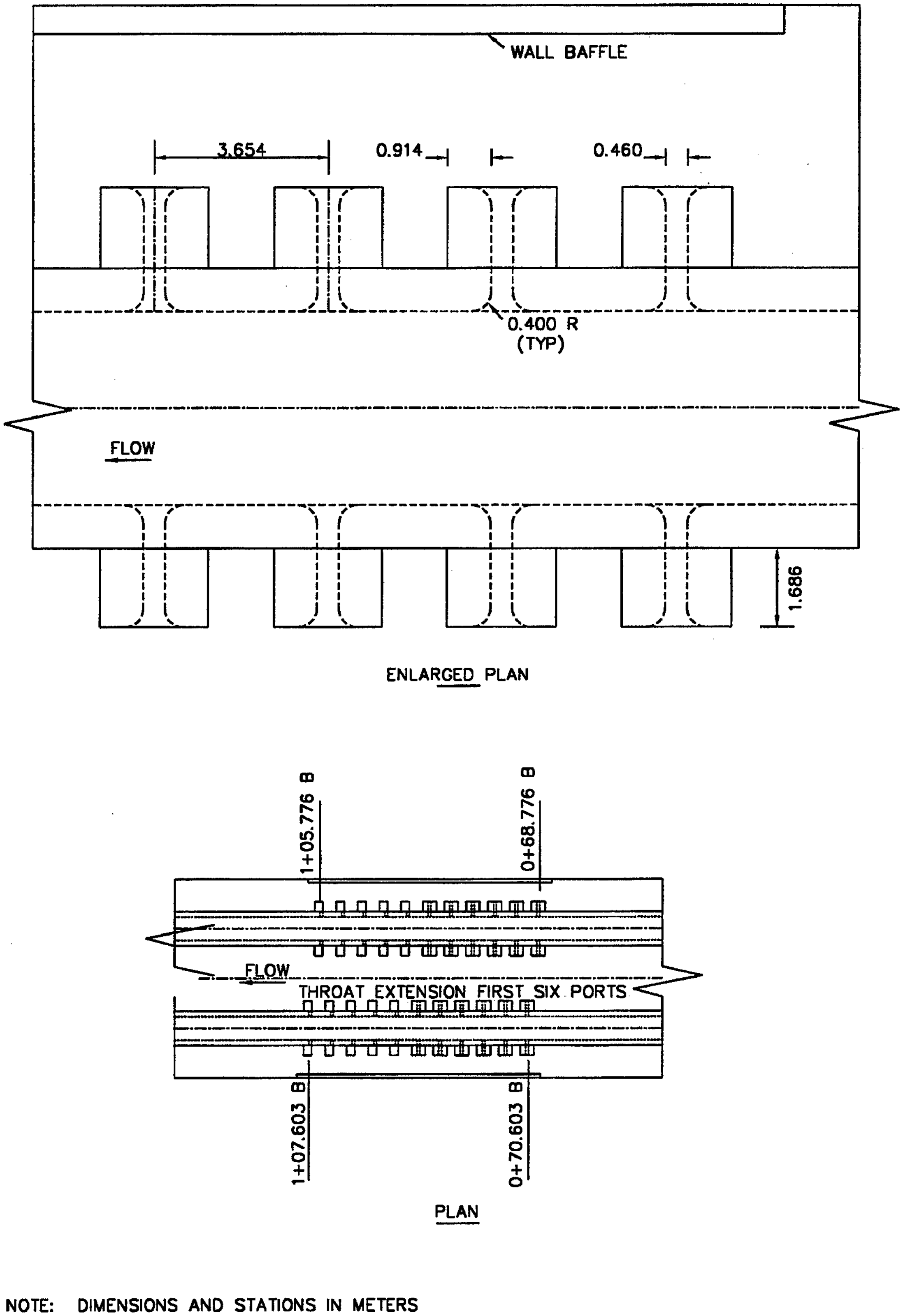
HAWSER FORCES
DURING FILLING
TYPES 1–4 CHAMBER DESIGNS



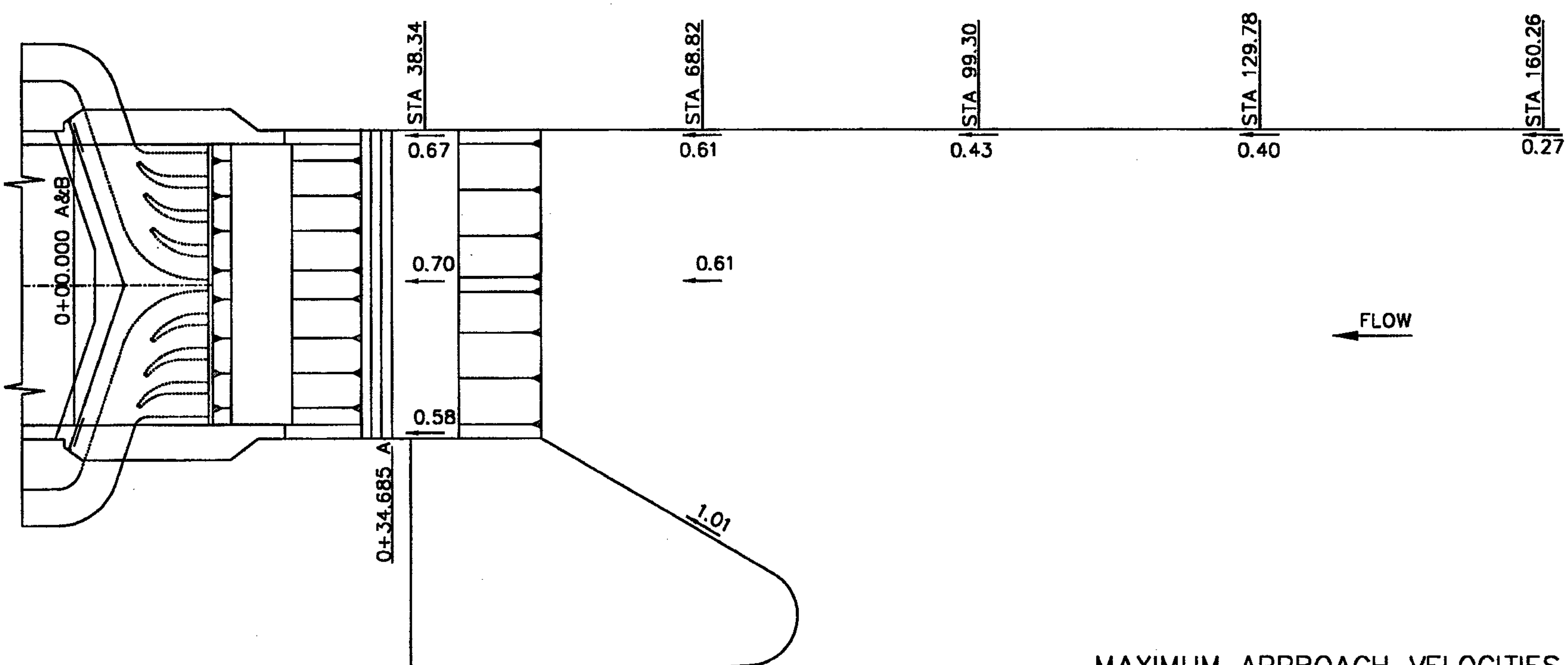


LEGEND	
SYMBOL	VALVE SCHEDULE, MIN
○	2
□	4
△	8
LINE TYPE	DESIGN TYPE
————	1
—·—·—	2
— —	3
-------	4

HAWSER FORCES
DURING EMPTYING
TYPES 1–4 CHAMBER DESIGNS

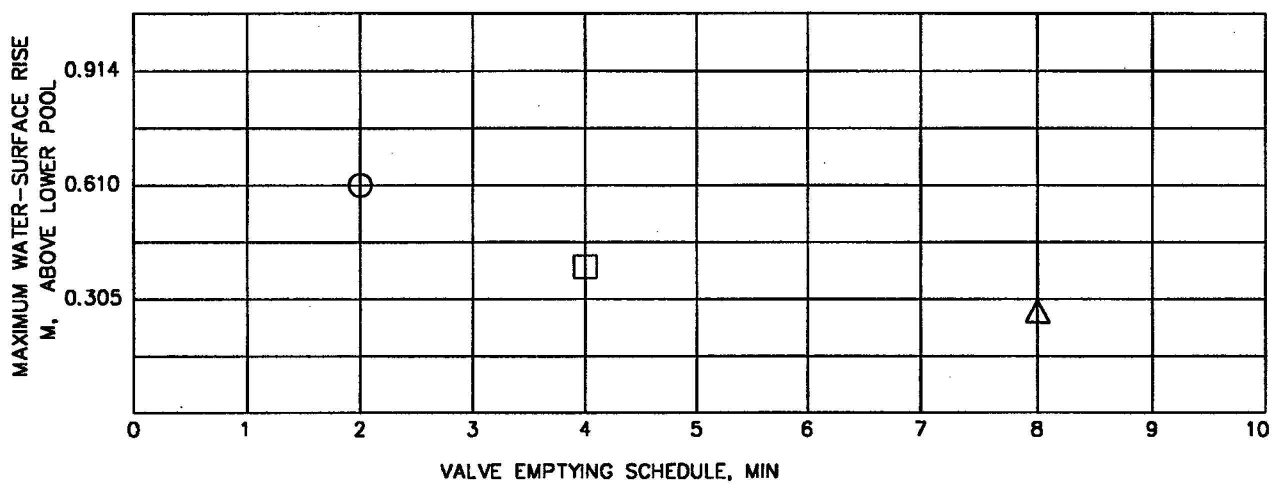


TYPE 4 CHAMBER DESIGN

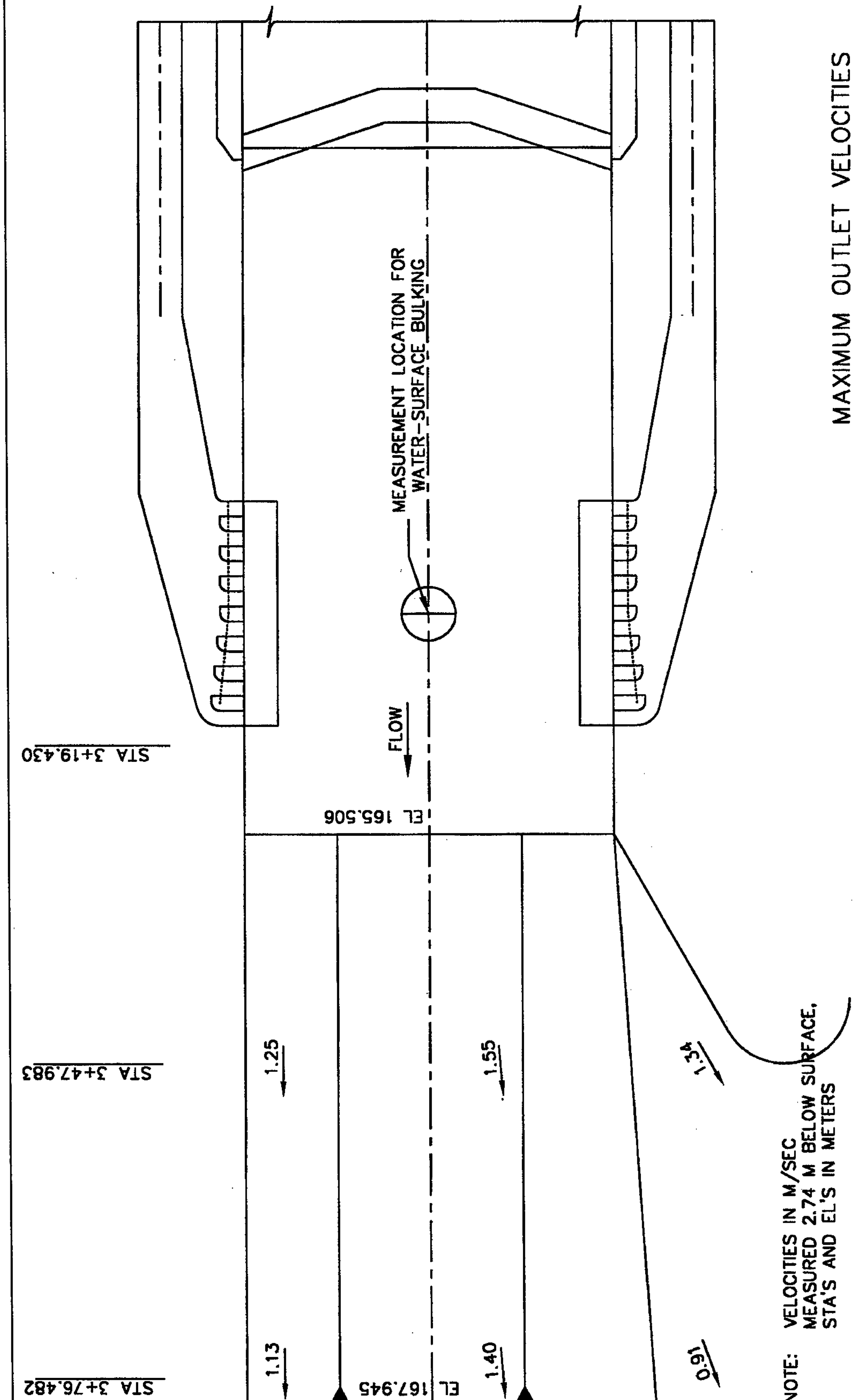


NOTE: VELOCITIES ARE IN M/SEC
MEASURED 2.74 M BELOW SURFACE,
STA'S AND EL'S IN METERS

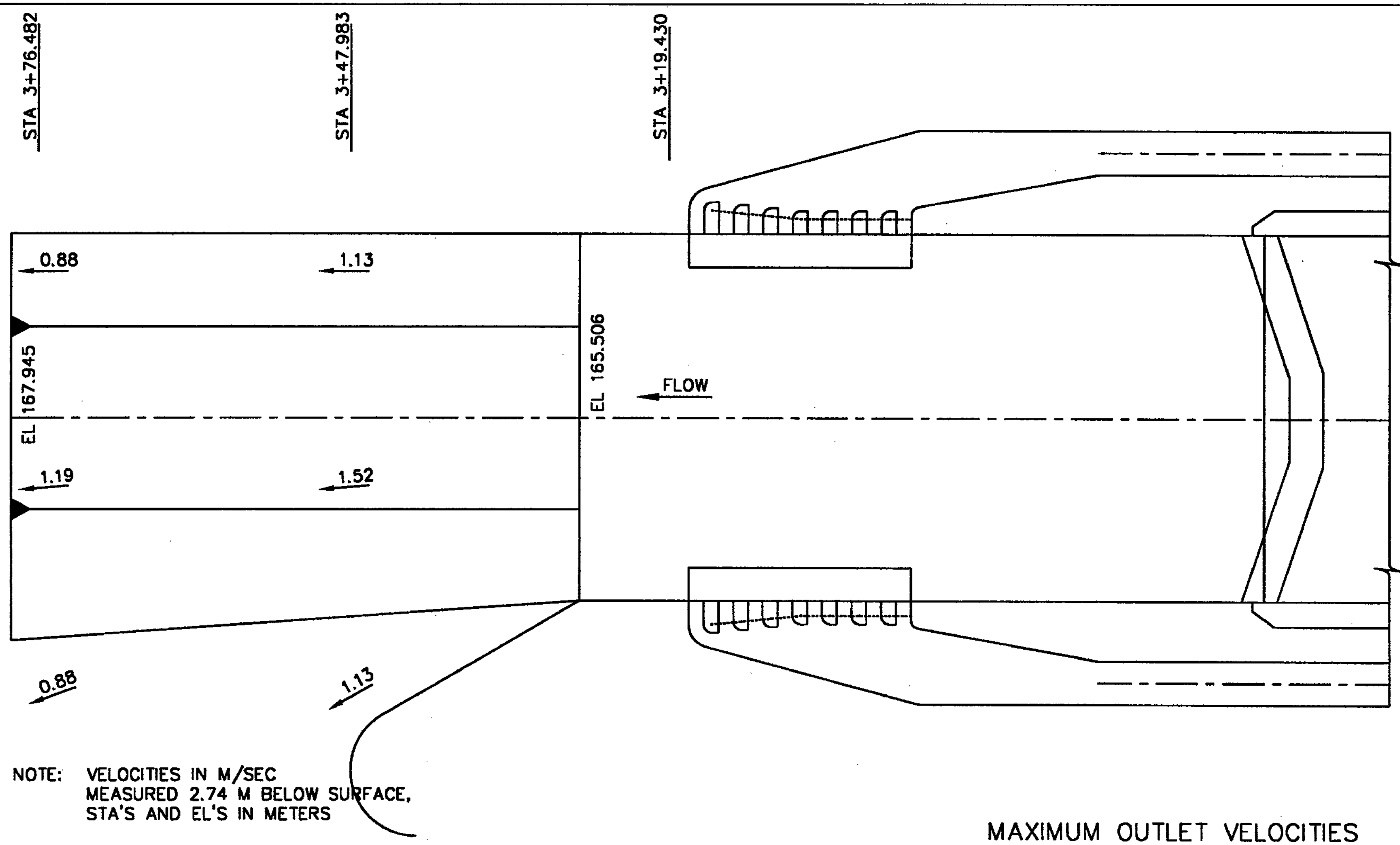
MAXIMUM APPROACH VELOCITIES
TYPE 3 APPROACH DESIGN
TYPE 1 CHAMBER DESIGN
UPPER POOL EL 179.832
LOWER POOL EL 172.315
4-MIN. VALVE OPERATION



OUTLET BULKING
TYPE 1 DESIGN
UPPER POOL EL 179.832
LOWER POOL EL 172.315

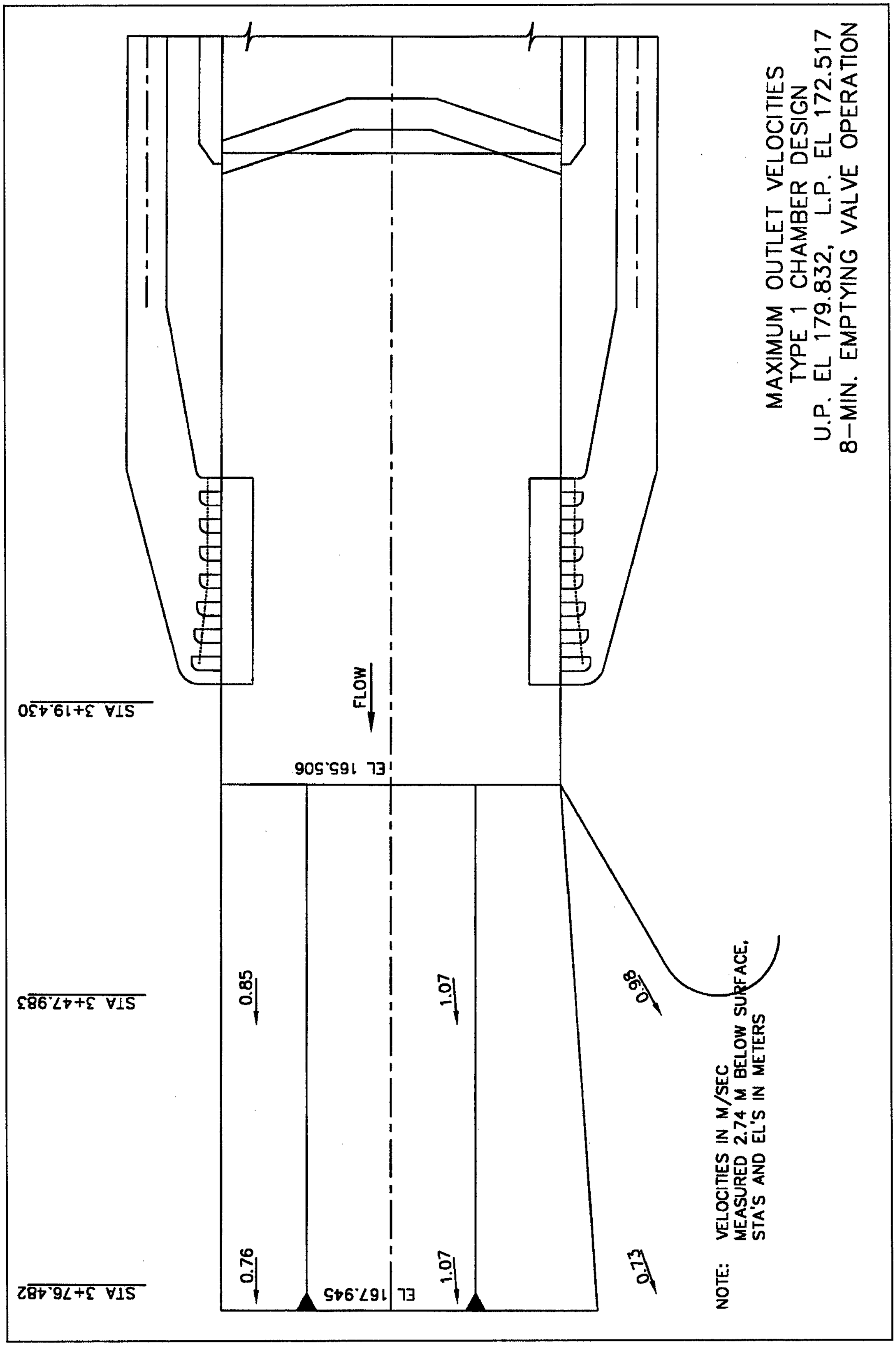


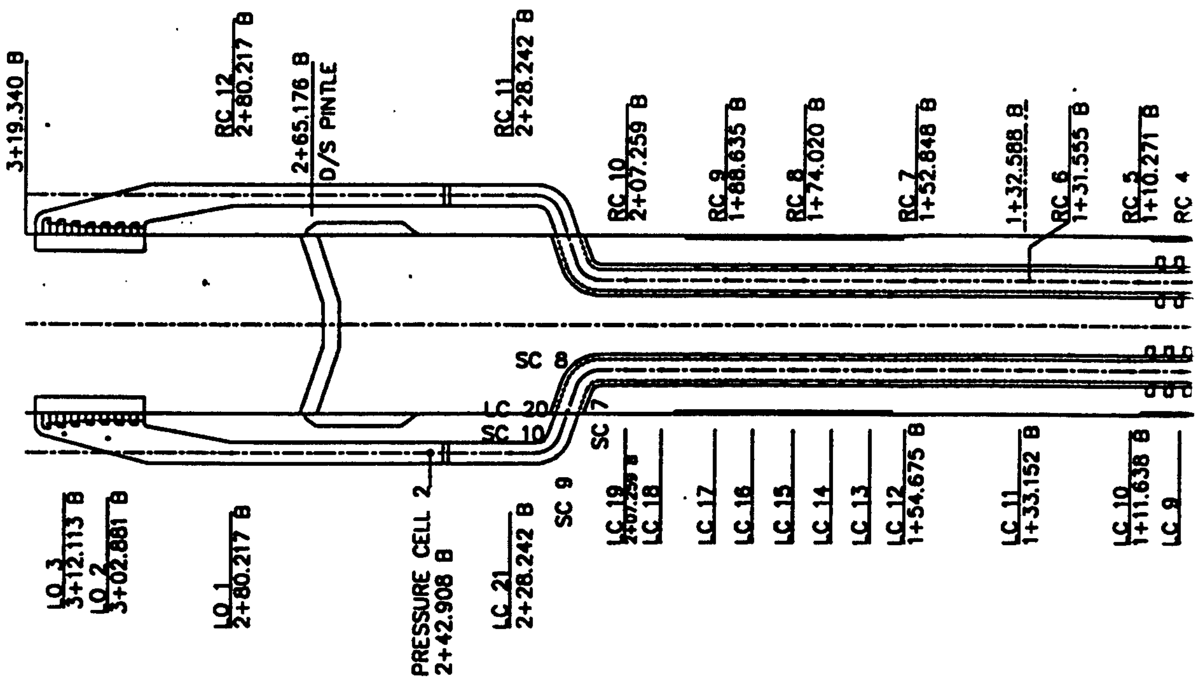
MAXIMUM OUTLET VELOCITIES
TYPE 1 CHAMBER DESIGN
U.P. EL 179.832, L.P. EL 172.517
2-MIN. EMPTYING VALVE OPERATION



NOTE: VELOCITIES IN M/SEC
MEASURED 2.74 M BELOW SURFACE,
STA'S AND EL'S IN METERS

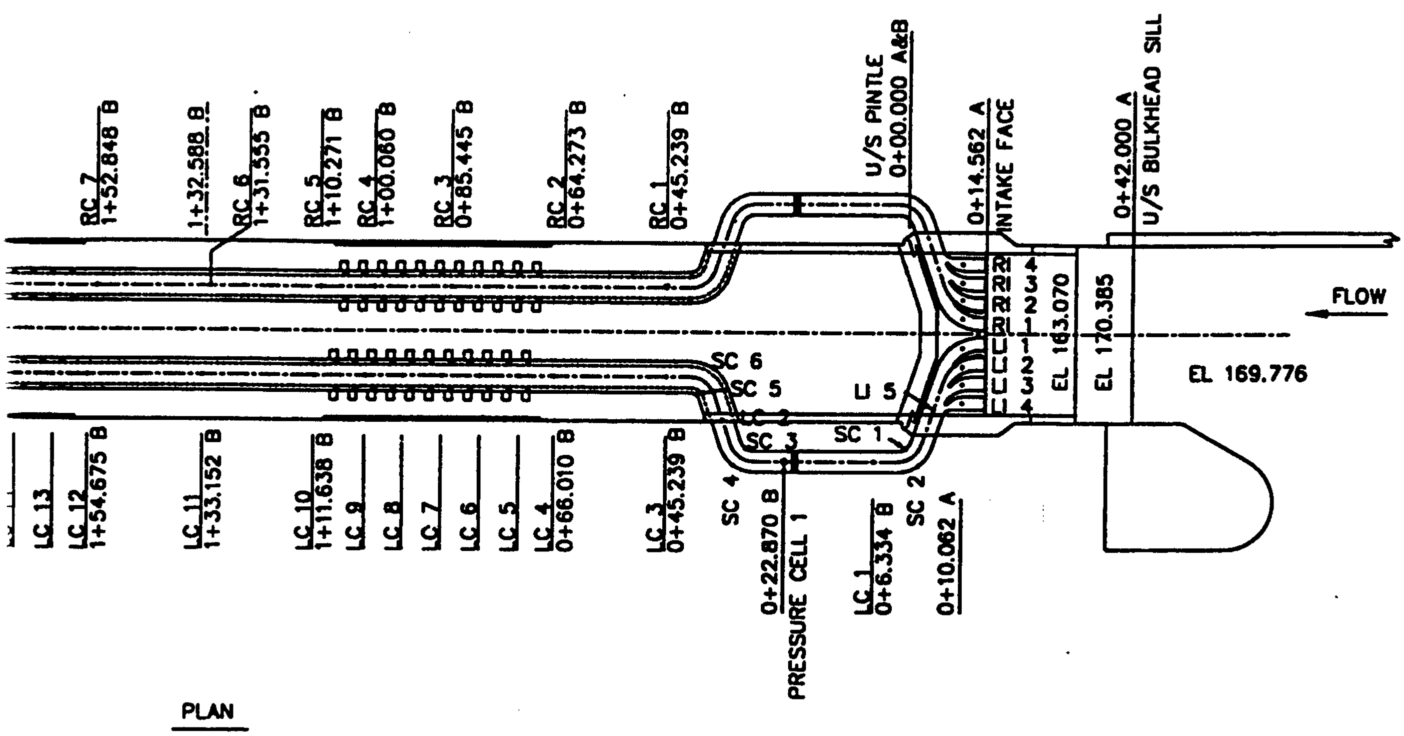
MAXIMUM OUTLET VELOCITIES
TYPE 1 CHAMBER DESIGN
U.P. EL 179.832, L.P. EL 172.517
4-MIN. EMPTYING VALVE OPERATION


MAXIMUM OUTLET VELOCITIES
TYPE 1 CHAMBER DESIGN
U.P. EL 179.832, L.P. EL 172.517
8-MIN. EMPTYING VALVE OPERATION
STA 3+19.430
STA 3+47.983
STA 3+76.482
FLOW
EL 165.506
EL 167.945
0.85
1.07
0.98
0.76
1.07
0.73
NOTE: VELOCITIES IN M/SEC
MEASURED 2.74 M BELOW SURFACE,
STA'S AND EL'S IN METERS

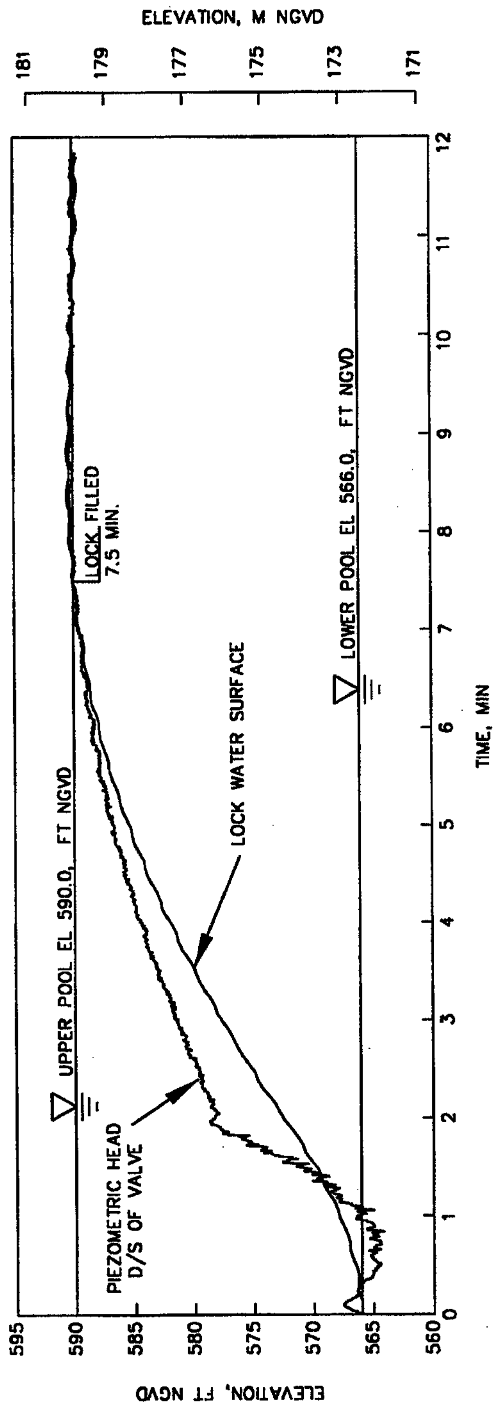


PLAN

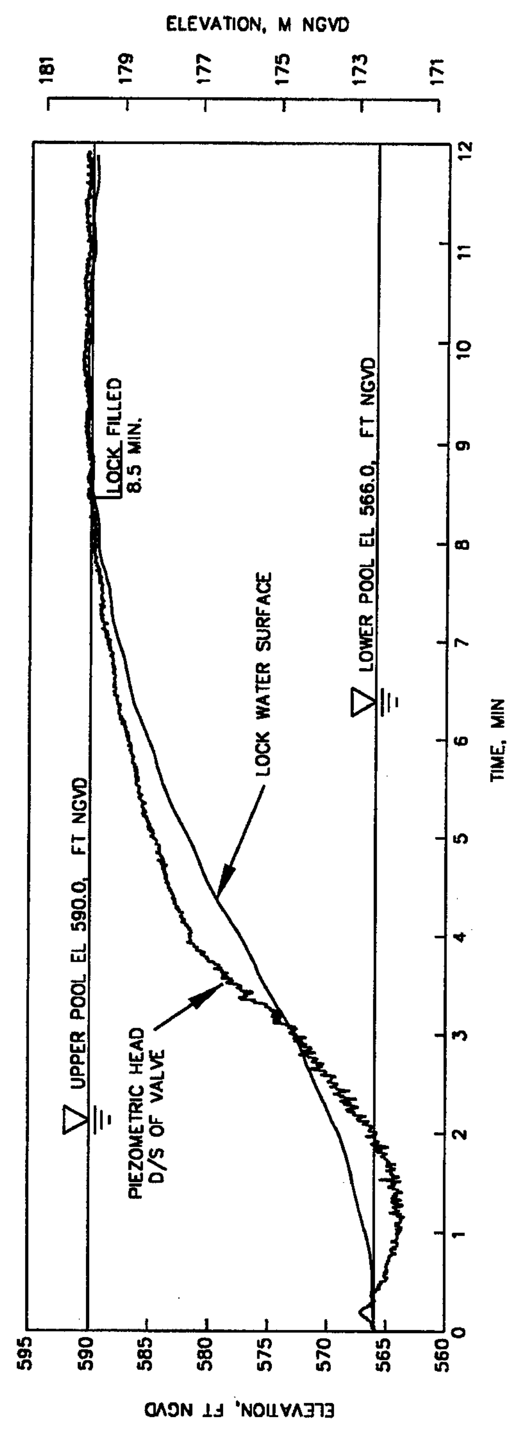
NOTE: DIMENSIONS AND STATIONS IN METERS



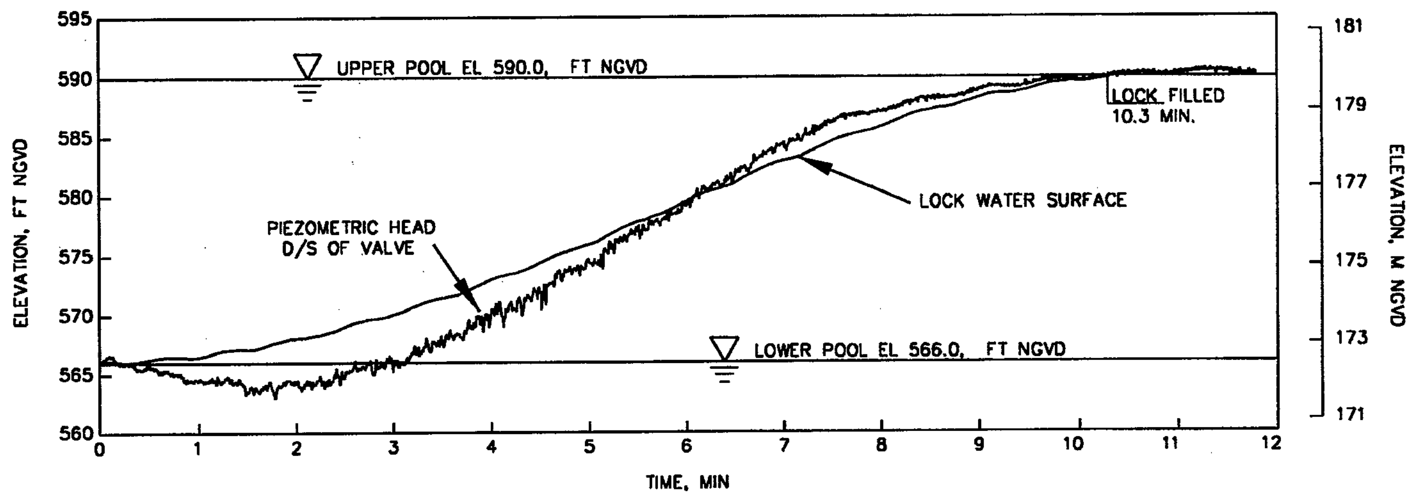
PIEZOMETER LOCATIONS
TYPE 1 FILLING AND EMPTYING SYSTEM



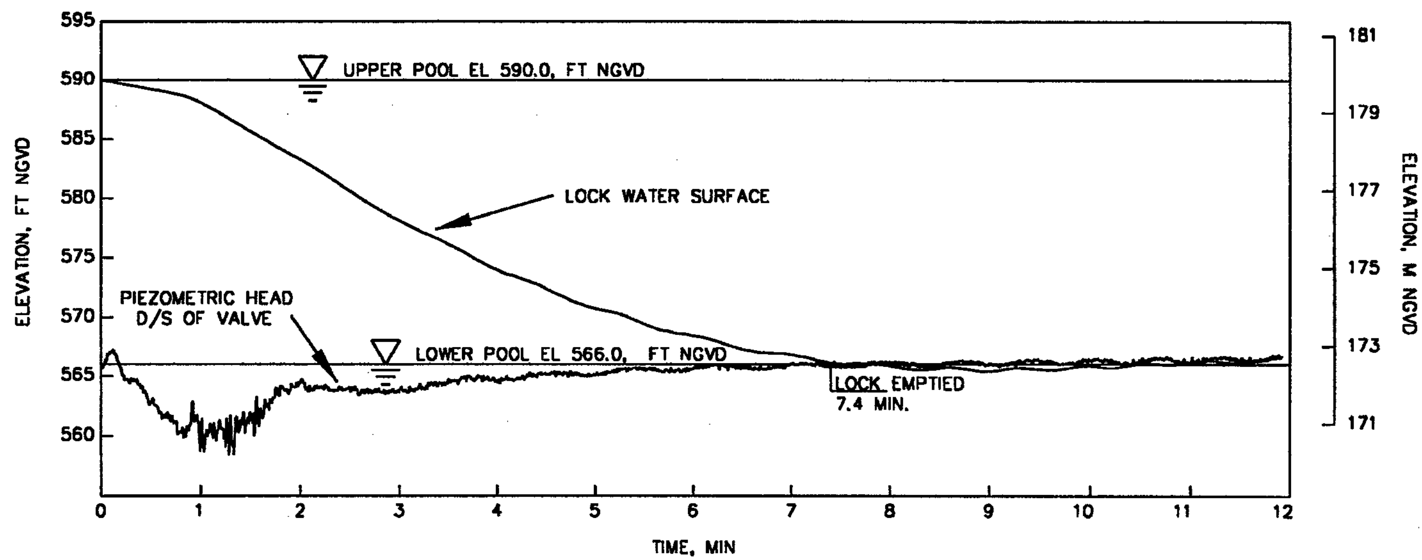
CULVERT PRESSURES DURING FILLING
TYPE 1 CHAMBER DESIGN
2-MIN NORMAL FILL



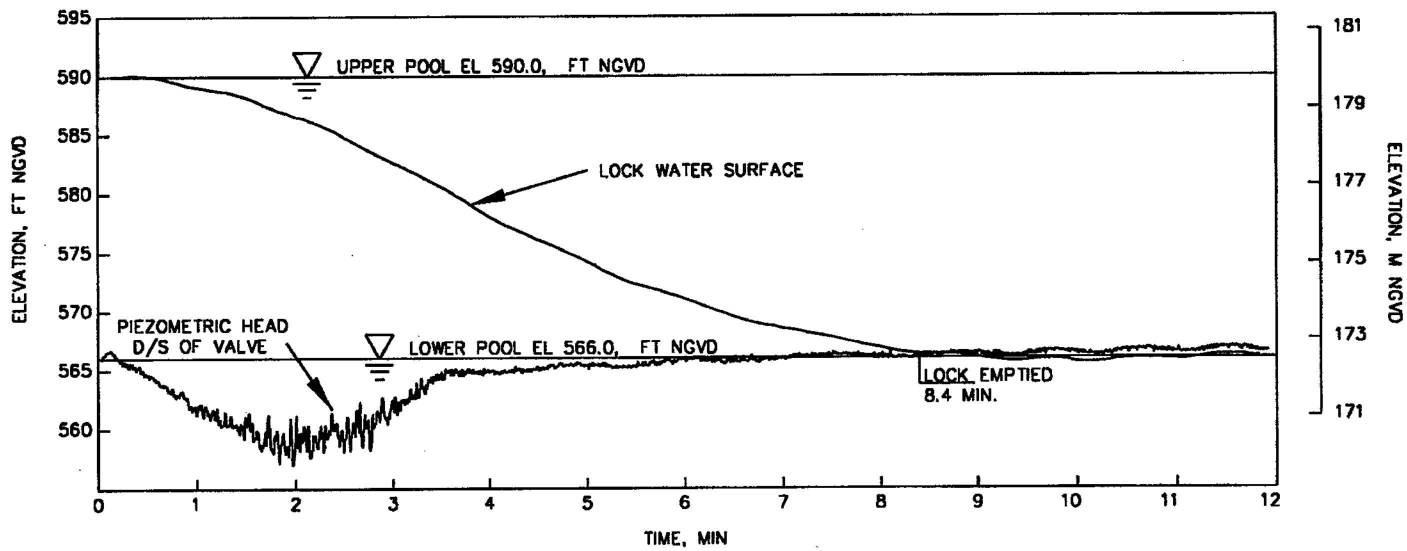
CULVERT PRESSURES DURING FILLING
TYPE 1 CHAMBER DESIGN
4-MIN NORMAL FILL



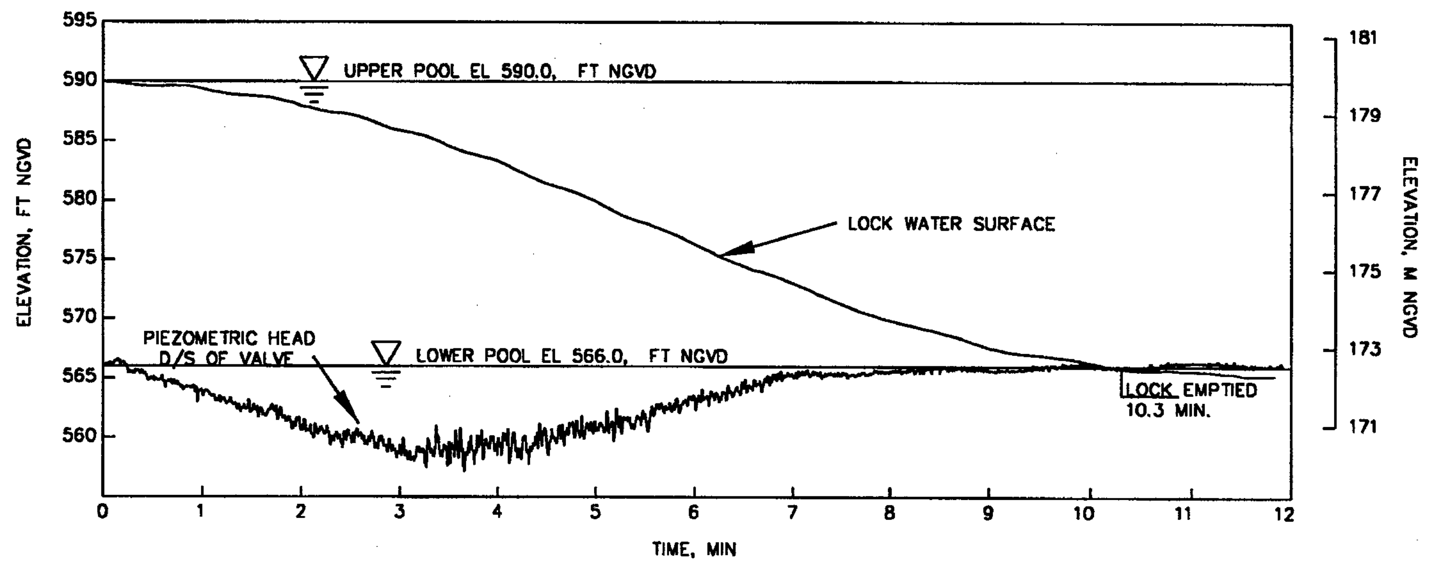
CULVERT PRESSURES DURING FILLING
TYPE 1 CHAMBER DESIGN
8–MIN NORMAL FILL



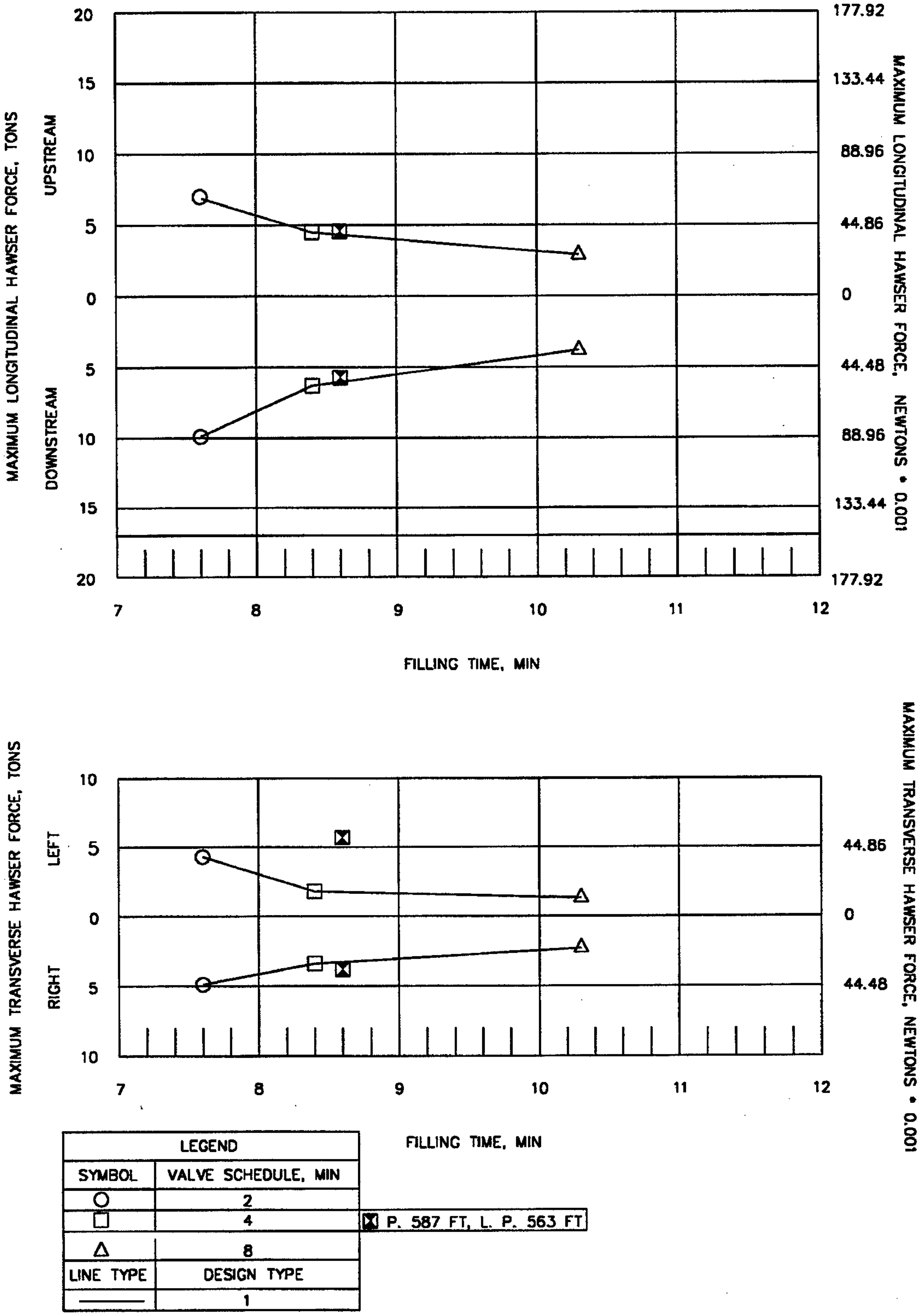
CULVERT PRESSURES DURING EMPTYING
TYPE 1 CHAMBER DESIGN
2-MIN NORMAL EMPTY



CULVERT PRESSURES DURING EMPTYING
TYPE 1 CHAMBER DESIGN
4-MIN NORMAL EMPTY



CULVERT PRESSURES DURING EMPTYING
TYPE 1 CHAMBER DESIGN
8–MIN NORMAL EMPTY



HAWSER FORCES
DURING FILLING
RAISED FLOOR SIMULATION

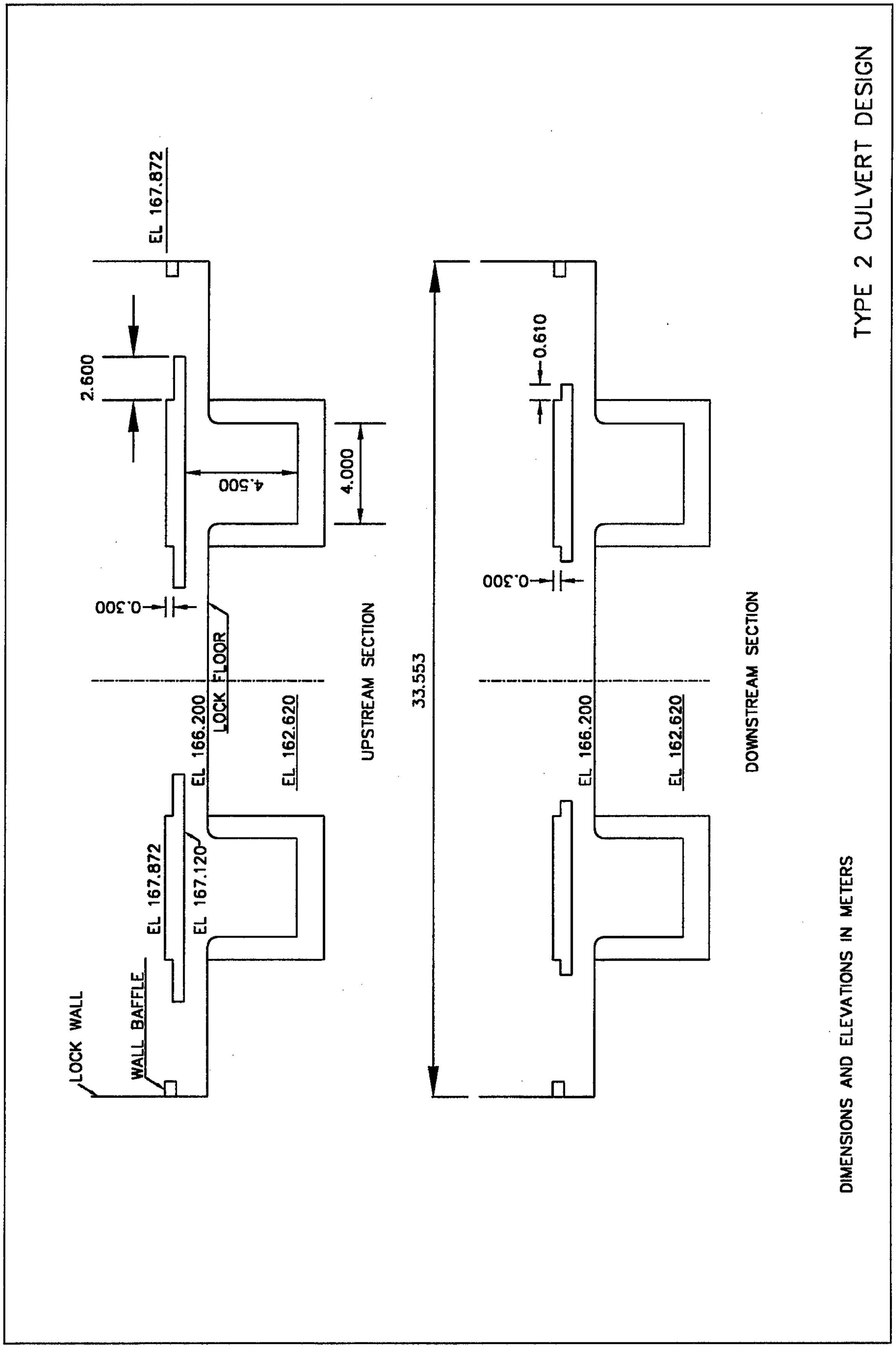
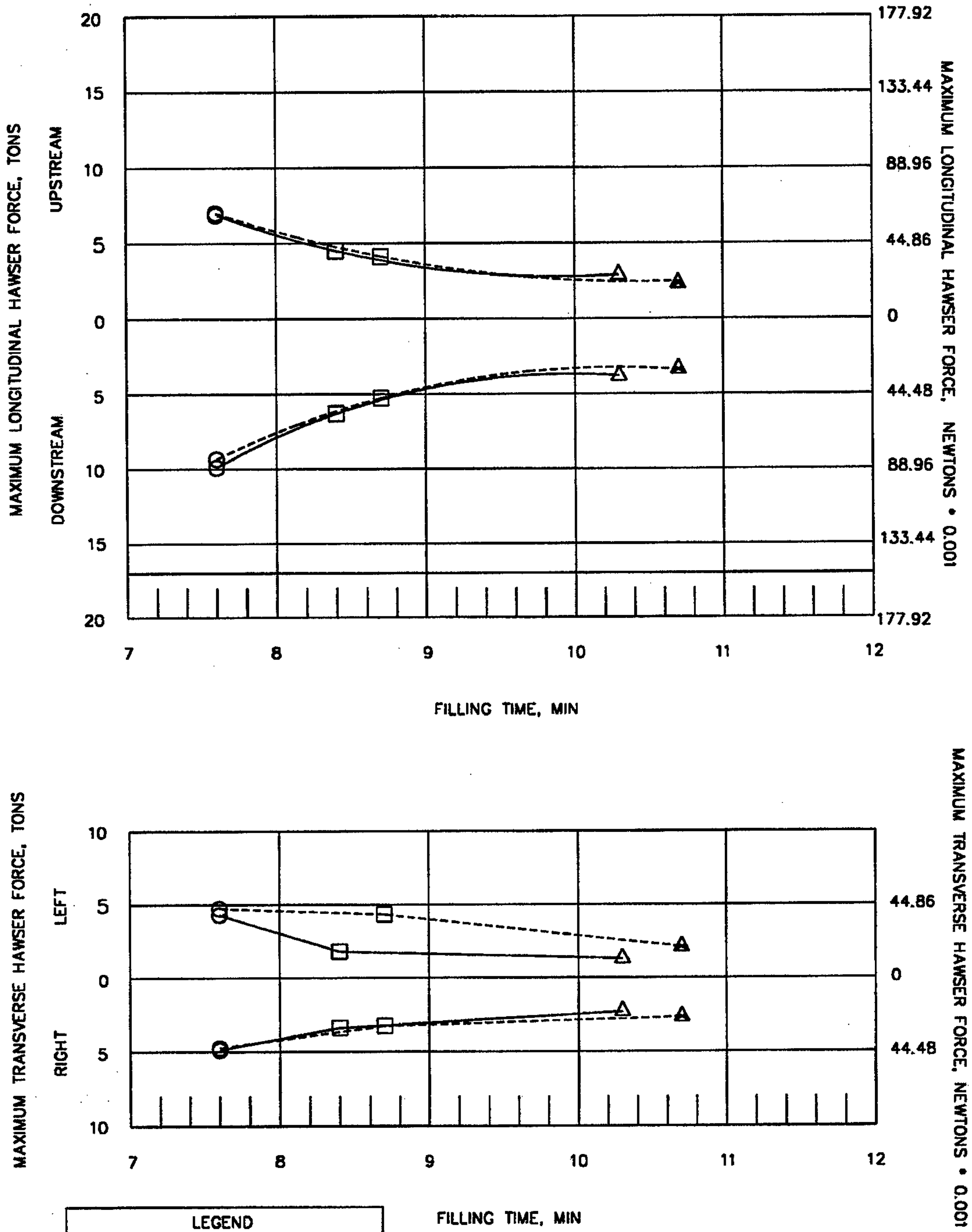

TYPE 2 CULVERT DESIGN
EL 167.872
2.600
4.500
4.000
0.300
LOCK FLOOR
EL 166.200
EL 162.620
UPSTREAM SECTION
33.553
0.610
0.300
EL 166.200
EL 162.620
DOWNSTREAM SECTION
LOCK WALL
WALL BAFFLE
EL 167.872
EL 167.120
DIMENSIONS AND ELEVATIONS IN METERS

Plate 36



LEGEND	
SYMBOL	VALVE SCHEDULE, MIN
○	2
□	4
△	8
LINE TYPE	DESIGN TYPE
————	1
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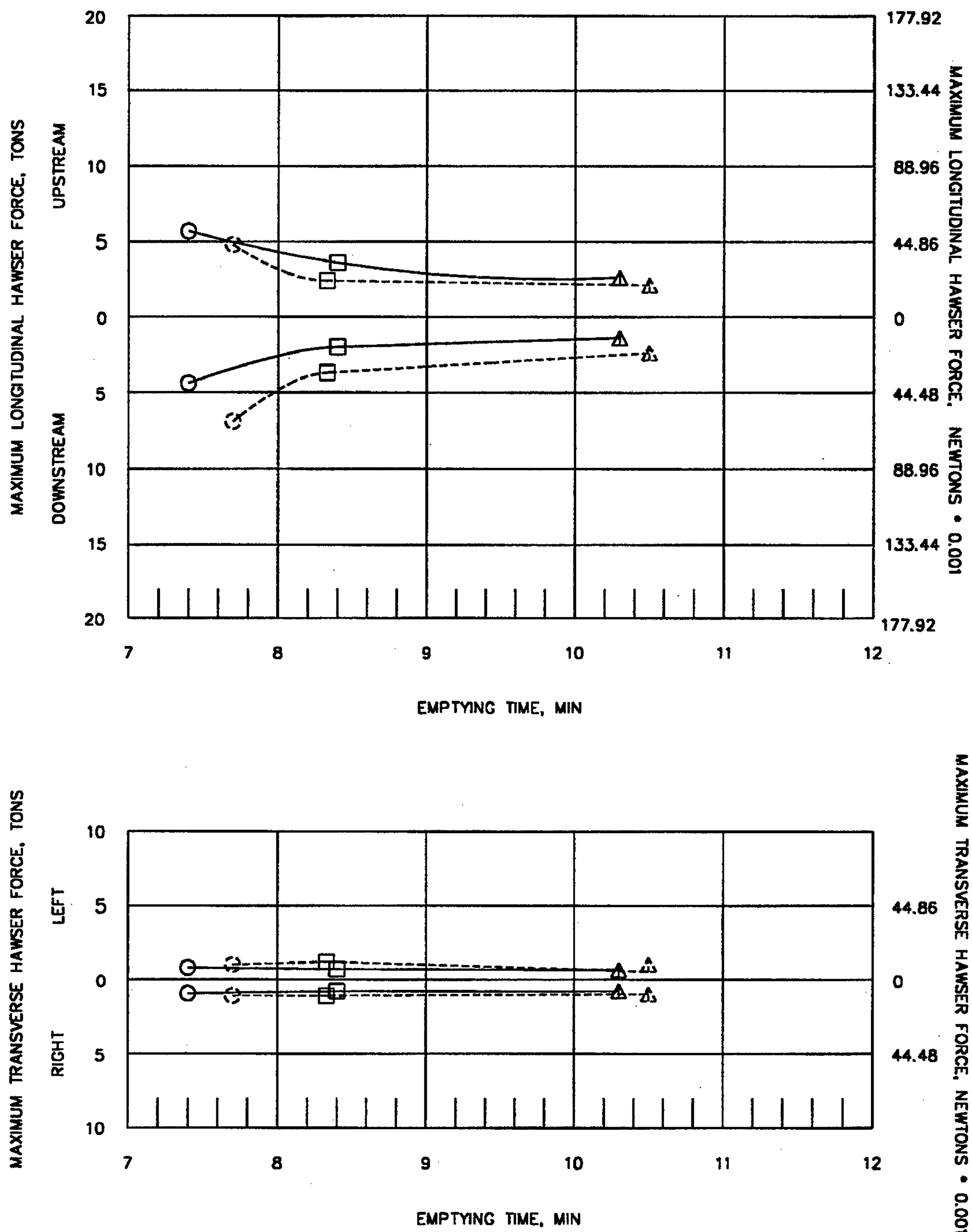
HAWSER FORCES
DURING FILLING
TYPES 1 AND 5 CHAMBER DESIGNS



LEGEND	
SYMBOL	VALVE SCHEDULE, MIN
○	2
□	4
△	8
LINE TYPE	DESIGN TYPE
———	1
-------	5

HAWSER FORCES
DURING EMPTYING
TYPES 1 AND 5 CHAMBER DESIGNS

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13. ABSTRACT ***(Maximum 200 words)***

This report documents the laboratory model investigation of the lock filling and emptying system for lock addition planned for the Marmet Navigation Project. This project is located on the Kanawha River in the U.S. Army Engineer District, Huntington. The filling and emptying system consists of an innovative through-the-sill intake and in-chamber longitudinal culverts. This system is less expensive than the conventional side port filling and emptying system. The model results revealed that the flow conditions in the upper approach during filling operations could be improved by lowering the upstream maintenance sill and streamlining the approach to the intakes. The original design filling and emptying system was found to perform satisfactorily for the design lift of 7.315 m (24 ft) and a 4-min valve operation. No excessive surface turbulence occurred in the chamber, and the maximum hawser forces experienced by a three- by four-barge arrangement moored inside the chamber were considered acceptable. No changes were made to the discharge outlet design.

14. SUBJECT TERMS
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Innovative lock design
Kanawha River
Lock filling and emptying system
Marmet Locks and Dam
Navigation lock

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